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Innovative Noise Analysis and Abatement Design for Large Mining Vehicles

Frank Angione
University of Windsor

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Innovative Noise Analysis and Abatement Design for Large Mining Vehicles

By

Frank Angione

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2015

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Innovative Noise Analysis and Abatement Design for Large Mining Vehicles

By

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DECLARATION OF ORIGINALITY

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ABSTRACT

GoldCorp Porcupine mine, located in the city centre of Timmins, Ontario, is Timmins’ largest industrial operation and is located near to residential receptors. Given this, noise compliance to the Ministry of the Environment guidelines is a concern for GoldCorp. A significant source of environmental noise is the Caterpillar 785B haul trucks, which transport raw materials along the haul road and past the residential receptors. The goal of this research is to analyze and design an effective abatement plan to lessen the noise impact of the haul trucks used at the GoldCorp mine. The novelty of the research is the use of advanced noise source identification (NSI) technology and array hardware for the identification and ranking of the noise sources to eliminate the guesswork for the abatement design. The outcome is the design of a detailed and effective abatement strategy that has since been implemented on the entire haul truck fleet.
ACKNOWLEDGEMENTS

Special thanks is extended to GoldCorp for their aid in the access to the 785B haul trucks tested and cooperation in the arrangement of test areas.
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<th>Description</th>
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<tr>
<td>MOE</td>
<td>Ministry of the Environment</td>
</tr>
<tr>
<td>NSI</td>
<td>Noise source identification</td>
</tr>
<tr>
<td>SPL ($L_p$)</td>
<td>Sound pressure level</td>
</tr>
<tr>
<td>NAH</td>
<td>Nearfield acoustic holography</td>
</tr>
<tr>
<td>STSF</td>
<td>Spatial transformation of sound field</td>
</tr>
<tr>
<td>SONAH</td>
<td>Statistically optimised nearfield acoustic holography</td>
</tr>
<tr>
<td>DAS</td>
<td>Delay and sum</td>
</tr>
<tr>
<td>DAMAS</td>
<td>Deconvolution approach for the mapping of acoustic sources</td>
</tr>
<tr>
<td>CSM</td>
<td>Cross-spectral matrices</td>
</tr>
<tr>
<td>SADA</td>
<td>Small aperture directional array</td>
</tr>
<tr>
<td>QFF</td>
<td>Quiet flow facility</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle-of-attack</td>
</tr>
<tr>
<td>DR</td>
<td>Diagonal Removal</td>
</tr>
<tr>
<td>$f$ or $\omega$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength of a sound wave</td>
</tr>
<tr>
<td>$W$</td>
<td>Sound power</td>
</tr>
<tr>
<td>$W_0$</td>
<td>Reference sound power</td>
</tr>
<tr>
<td>$L_W$</td>
<td>Sound power level</td>
</tr>
<tr>
<td>$P$</td>
<td>Sound pressure</td>
</tr>
</tbody>
</table>
$P_o$  Reference sound pressure 
$r$  Distance from the sound source 
$DI\theta$  Directivity index 
$I$  Sound intensity 
$I_o$  Reference sound intensity 
$L_l$  Sound intensity level 
$S(r)$  Acoustic intensity vector 
$v_o$  Velocity amplitude 
$\psi$ or $f(\vec{x}, t)$  Three-dimensional wave field 
$t$  Time 
$G(r|r_5)$  Green’s function 
$r_s$  Distance from source to surface S 
$T$  Finite time duration 
$k$  Wave number 
$\partial G/\partial n$  Derivative of the Green’s function with respect to $r_5$ 
$\xi_1, \xi_2, \xi_3$  Spatial coordinates 
$x, y, z$  Cartesian rectangular coordinates 
$\Delta_m$  Time delay 
$s(t)$  Signal emitted from a sound source (may just be point) 
$\vec{x}$  Location of sound source 
$y(t)$  Waveform 
$w_m$  Amplitude weighting
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$ z(t) $</td>
<td>DAS beamformer output</td>
</tr>
<tr>
<td>$ \zeta $</td>
<td>Direction of propagation</td>
</tr>
<tr>
<td>$ \alpha $</td>
<td>Slowness vector</td>
</tr>
<tr>
<td>$ W(k) $</td>
<td>Array pattern</td>
</tr>
<tr>
<td>$ h(\vec{x}, t) $</td>
<td>System impulse response</td>
</tr>
<tr>
<td>$ G_{mm'} $</td>
<td>Elements of a cross-spectral matrix</td>
</tr>
<tr>
<td>$ \tilde{G} $</td>
<td>Cross-spectral matrix</td>
</tr>
<tr>
<td>$ \hat{e} $</td>
<td>Steering vector</td>
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<tr>
<td>$ e_m $</td>
<td>Steering vector corresponding to microphone $ m $</td>
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<tr>
<td>$ a_m $</td>
<td>Shear layer refraction amplitude correction for $ e_m $</td>
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<tr>
<td>$ \tau_m $</td>
<td>Time of signal propagation from a point on the source plane to microphone $ m $</td>
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<td>Standard beamforming output</td>
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<td>Shading matrix</td>
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<td>$ w_m $</td>
<td>Shading value corresponding to microphone $ m $</td>
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<td>Pressure transform</td>
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<tr>
<td>$ \tilde{X} $</td>
<td>Matrix of $ X_n $ components</td>
</tr>
<tr>
<td>$ X_n $</td>
<td>Noise source at grid point $ n $ with levels defined at the array</td>
</tr>
<tr>
<td>$ N $</td>
<td>Number of independent sources at different positions</td>
</tr>
<tr>
<td>$ \hat{A} $</td>
<td>DAMAS matrix</td>
</tr>
<tr>
<td>$ A_{nn'} $</td>
<td>Components of DAMAS matrix</td>
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<tr>
<td>$ \hat{Y} $</td>
<td>Matrix of beamformer output</td>
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$Y_n$  Components of $\hat{P}$ when focused on grid point $n$

$m$  Microphone number

$n$  Grid point number

$i$  Iteration number
I. Introduction

The GoldCorp Porcupine mine is a large scale open pit gold mine which is located near the city centre of Timmins, Ontario and is in very close proximity to many sensitive receptors. These include low and high density residential and commercial receptors. This is a concern to GoldCorp in regard to their interest to be a good corporate neighbour and also their need to maintain compliance with Ontario’s Ministry of the Environment (MOE) guidelines for noise emissions. As part of the mine’s operations, a significant source of environmental noise is the traffic along the haul road which is used to transport material from the extraction operations to the processing facility which is approximately 5 km away. This haul road, which is located as close as 700 metres to residential areas, is a focus for needed noise control. The potential for the use of noise barrier walls has already been maximized and it has been recognized that other methods of noise control are required if the mining operations are to comply with the MOE noise guidelines when the mine operations are operating at its fullest capacity.

Given the above, the focus for additional noise control is directed to the haul trucks, which continuously operate back and forth along the haul road. The entire fleet of trucks is comprised of the Caterpillar 785B haul vehicle. This vehicle has many potential sources of noise including engine intake and exhaust noise, engine shell noise and rolling noise to name some. The focus for this research is to perform a detailed analysis to identify and rank the varying sources of noise using advanced analysis techniques and then design an abatement plan that is effective, cost efficient and is practical from a maintenance perspective. Once complete and proven effective using a representative truck, the intent is to outfit the entire haul truck fleet with the abatement plan.
The novelty of the noise analysis performed is the use of noise source identification (NSI) instrumentation and the associated algorithms. NSI is an advanced acoustical technique that uses an array of microphones to produce visual noise maps, which can be overlaid on images of the source; in this case, the haul truck. These noise maps are analogous to a thermal image, which is used to show temperature variations. In this case, the colours shown on the noise map represent varying amplitude of the noise emissions of the source. The noise maps can also show the specific numerical contribution of sound pressure level (SPL) or sound power level for a specified region. This data is often given in overall levels or as 1/3-octave band levels. Using the SPL or sound power level spectral data and contour plots of isolated sub-sources, the ranking and relative impact of each sub-source can be quantified. For this research, a NSI analysis is utilized to identify the significant noise contributors for the 785B mining vehicle and to determine their relative impacts on the overall noise emission of the vehicle.

Using the insight given by this NSI investigation, specifically the location and relative rankings of the noise sources, a noise abatement plan is to be developed for the 785B truck. Noise abatement is often a trial and error process for complex sources such as the 785B mining vehicle. Using the NSI analysis proposed in this study, the guesswork for the identification of the noisiest regions of emission is largely removed.

Following the exercise of noise source identification and ranking for the haul truck, and design of noise abatement, the haul truck is to be re-evaluated for noise emissions. That is, the effectiveness of the proposed noise abatement is quantified using the same NSI techniques.
In summary, the plan and intended outcomes for this thesis are as follows:

- A comprehensive literature review of the history and current state of art for NSI techniques will be detailed. This will include discussions of applicability to the methods used in this research where relevant.

- Define a detailed experimental test procedure using NSI methodologies for the evaluation of the 785B mining vehicle.

- Analysis of preliminary results for the detection and ranking of significant sub-sources.

- Propose a custom abatement treatment to be validated using NSI techniques and SPL measurements.

- Validate and quantify the impact of existing noise control currently employed and the proposed noise abatement treatment.

- Recommend an overall noise abatement treatment for the reduction of noise emissions from the 785B haul vehicle.
II. Literature Survey

2.1 Noise Source Identification

Noise source identification has advanced substantially in the last 30 years through advancements and discoveries in array processing methodologies. Many researchers have applied beamforming and spatial filtering algorithms to acoustical applications for source identification. Studies in areas such as aeroacoustics and industrial noise control have pushed the forefront of array processing techniques development. Noise source identification has become an essential tool with the requirement for effective as well as efficient noise control in industry. This necessity motivated various researchers to advance existing methodologies and strive to develop new and improved algorithms to achieve the most accurate and precise approach to NSI. The work accomplished by key researchers, including Hald, Brooks, Humphreys, Ginn, and Dougherty are responsible for the advances in array processing, as it exists today. Researchers, such as those previously mentioned, have pushed array processing methodologies and NSI to new heights through studies for a wide-range of applications. Aerospace, industrial noise control, and automotive are just some of the industries relying on NSI, making it a widely accepted and necessary technique. Defining research will be covered in this study to provide a detailed understanding of the novelty and evolution of both NSI and array processing techniques.

Key research findings and ongoing advancements in methodologies are the basis of the NSI techniques utilized today. Early nearfield acoustic holography (NAH) methods served as the early foundation of array processing techniques and NSI. Hald, has published many research studies focusing on the advancements and applications of NAH, ranging
from techniques such as spatial transformation of sound field (STSF) to statistically optimised nearfield acoustic holography (SONAH) [1]–[3]. Hald was involved in the field of beamforming research and its applications [3], [4]. In 1989, Hald authored a technical review of the STSF technique outlining the mathematics behind the methodology as well as the ability of STSF to translate a sound field plane to a plane closer to the source through NAH and farther from the source through Helmholtz’s integral equation. These theorems and applicable algorithms are the groundwork of modern sound mapping techniques.

Two of Hald’s publications were featured in Brüel & Kjær’s technical review “Surface Microphone NAH and Beamforming using the same array” released in 2005. One of the publications, “Patch Nearfield Acoustical Holography Using a New Statistically Optimal Method”, introduced the SONAH method as an expansion of NAH, which overcame the limitations of traditional NAH data acquisition. This publication is also featured in the 2003 Proceedings of Inter-noise. Previously, NAH required the array to encompass the entire sound source under consideration; for large sound sources (i.e. mining vehicles), this would require a large quantity of measurement points that would typically not be feasible. A major advantage of the newly developed SONAH methodology is its capability of utilizing an array that is smaller than the sound source. This advancement is achieved through SONAH having the ability to perform plane-to-plane transformations directly without the use of a spatial fast Fourier transform FFT, as done in NAH algorithms [1]. Further, the SONAH technique suppresses the spatial window effects, thus allowing a measurement to be acquired for a portion of a large sound source while still maintaining an acceptable level of error, which is not currently possible with NAH. This conclusion was verified through experiments conducted by Hald. The sound source under evaluation
was the side of a steel track of a large Caterpillar track-type tractor. A measurement of a small Carrier Roller with a relatively low level of noise radiation was taken with a 10 by 12 element array, with a 10 cm spacing [1]. NAH and SONAH calculations were applied to the measurement area to obtain direct comparable results of the two methods. Figure 1 below illustrates the averaged particle velocity maps resulting from the NAH and SONAH calculations of the Carrier Roller. Figure 1 shows that the SONAH technique has suppressed the window effects that are clearly present with the traditional NAH technique. The simulation and practical results demonstrate the SONAH technique’s ability to perform acoustical holography with an array that is smaller than the sound source while still maintaining an acceptable level of error [1].

![Image](image1.png)

Figure 1 - Average Particle Velocity maps for the 1/12-octave bands 205-1454 Hz, A-weighted. [1]

The second publication by Hald in Brüel & Kjær’s technical review outlined the combined use of NAH and beamforming with a single optimised array to expand on the usable frequency range of data acquired with an array. It is difficult to use NAH for the entire frequency range due to the limitation to measure high frequency, which is dictated
by the wavelength of the sound in relation to the microphone spacing of the measurement grid. In order to obtain good results at a high frequency, the microphone spacing required would have to be very small, resulting in a large number of measurement points. Depending on the size of the sound source, the measurement could require thousands of measurement points, which is impractical. To describe it simply, beamforming is an algorithm that uses acquired propagating waveform data and applies spatial filtering in the data processing to estimate the origin of waveforms and separate waveforms originating from different locations. It does this with a smaller array and substantially fewer measurement points compared to other methods. However, the principle disadvantage of beamforming is poor resolution exhibited at low frequencies. NAH measurements require a regular grid array with equal spacing between the microphones. In addition, as stated previously, NAH requires the grid array to encompass the entire sound source while still being relatively close in distance to the source. Unlike NAH, beamforming is capable of acquiring a measurement from a large distance with an array much smaller than the sound source. Thus, a combination method with a single array utilizing both NAH’s superior resolution in the low frequency region as well as beamforming’s ability to acquire data with accuracy in the high frequencies with minimal measurement points was desired.

An optimal array was designed which is capable of being processed with both NAH and beamforming. The key to accomplishing this feat is SONAH, the expansion of NAH. With SONAH, an array smaller than the sound source can be utilized. With an array comprised of several identical random sectors, an optimal array is created for both methodologies. This array design is irregular for beamforming and yet still exhibits a repeated section that is ideal for SONAH. Hald tested the combined method with a sector
wheel array, consisting of 60 channels. Beamforming and SONAH measurements were taken of two loudspeakers emitting white noise. The SONAH measurements were attained at 12 cm from the two loudspeakers and the beamforming measurements were acquired at both 55 cm and 100 cm. Sound intensity level was then estimated on an 80 cm by 80 cm grid on the source plane [1]. Figure 2 illustrates the resulting sound intensity maps for the measurements with a single speaker active. It was determined that the SONAH technique is the preferred choice for frequencies up to approximately 1500 Hz, past which beamforming is recommended. It was concluded by Hald that the SONAH technique should be used to a maximum frequency of 1250 Hz, after which beamforming should be used for frequencies exceeding 1250 Hz in order to obtain the highest resolution over the entire frequency range. The results of this test verified that the combination of NAH and beamforming with a single array is the recommended method for performing NSI over a vast frequency range.
Figure 2 - 1/3 octave sound intensity maps for the measurements with only the speaker on the right excited by broadband random noise. The four rows represent Beamforming measurements from 100 and 55 cm distance, SONAH from 12 cm distance and measurements with a sound intensity probe at 7 cm distance. The 1/3 octave centre frequencies are shown at the top of the columns. Dynamic range is 15 dB. [1]

The release of a technical review by Brüel & Kjær in 2004, authored by Christensen and Hald, explained beamforming in great detail through the most basic beamforming method, Delay and Sum (DAS) [4]. DAS beamforming is a straightforward methodology where measured pressure signals are individually delayed and subsequently summed. Time delays are selected such that the signals associated with a plane wave will be aligned in the time domain prior to being summed. DAS is the foundation to beamforming methodologies, which has been expanded to develop more advanced methods with greater performance, capabilities, and accuracy.
Based on the findings during this technical review, beamforming has been utilized in a variety of applications. The use of beamforming for NSI to create sound maps include: a vehicle in a test hall and a wind tunnel, a large crane (for the purpose of large sound source NSI), and an engine at high frequencies (to display small source NSI capabilities). Measurements of a complete vehicle in the test hall and the wind tunnel both presented very similar difficulties. When performing array measurements, high frequencies have smaller wavelengths, and thus in order to apply NSI on a complete vehicle using NAH, a large number of measurement points would be required, since upper frequency range in NAH is limited by the grid spaces. With very small grid spacing and large sound sources, NAH becomes impractical due to the large number of measurement points required. In the test hall measurement scenario, one beamforming measurement with an irregular array positioned three to seven metres from the vehicle surface is all that is necessary to obtain a sound map accurately displaying the ‘hot spots’ of the noise-radiating regions with the highest contribution to overall noise. In both the test hall and the wind tunnel, a half-wheel array was used because the reflectiveness of the floor in both of the environments. A challenge in the wind tunnel, which was of no concern in the test hall, was acquiring the measurement at a sufficient distance from the source to refrain from disrupting the airflow. If NAH was used, it would have been required that the array be positioned close to the source within the airflow. The ability to take measurements from a larger distance using the beamforming technique is ideal for this type of measurement since the measurement plane cannot be positioned too close to the source. Both of these applications are well suited for beamforming. The capacity of being able to take a measurement from a larger distance
and acquire high frequency data with substantially less measurement points are key attributes in the appeal of the beamforming method.

Another application described in the beamforming technical review, by Christensen and Hald, was the measurements of a large crane using an array [4]. NSI measurements of large sound sources, such as cranes, were very impractical due to the vast amount of grid points required for NAH. With the introduction of beamforming a one metre in diameter wheel array with 42 channels, positioned seven metres from the large sound source obtained a complete and accurate sound map of the crane. Beamforming allowed for NSI of large sound sources to be possible. Previously with NAH, available resources at the time simply did not permit such applications. The calculation of thousands of measurement points is very time consuming, not to mention would require thousands of microphones to acquire the data. Beamforming methodologies allow for practical noise mapping of very large sound sources.

Christensen and Hald also performed NSI on an engine, specifically targeting the high frequencies [4]. Even though an engine is a smaller sound source, in order to obtain high frequency results, the grid spacing using NAH would need to be approximately two centimetres and would require 2500 measurement positions (microphones) to measure the entire engine. Instead, a one metre diameter 66-channel array positioned approximately 0.9 metres from the source was used with beamforming to accomplish this feat. Similar conclusions were drawn from the applications featured in this release of Brüel & Kjær’s “Beamforming Technical Review”. To summarize, utilizing the beamforming methodology significantly decreases the number of measurement positions required to obtain high frequency results, thus reducing the complexity of high frequency NSI.
measurements and accompanying calculations. In addition, measurements can be taken at larger distances from the source, allowing large sources to be measured. Beamforming can be utilized to overcome many of the limitations of NAH.

With beamforming’s versatility in utilization of small irregular arrays, it has become the most utilized methodology for NSI. Traditional DAS beamforming has since been advanced and new methodologies have been accepted. In 2004, a deconvolution approach for the mapping of acoustic sources (DAMAS), by Brooks and Humphreys, had provided assurance in deconvolution methods for beamforming applications through the achieved accuracy of results [5]. DAMAS is an extension of classical beamforming. Classical beamforming has replaced DAS beamforming, which simply involves spectral processing to form cross-spectral matrices (CSM) and phase shifting. Classical beamforming results are related to a source distribution through the general matrix formula:

\[ A\hat{\mathbf{x}} = \mathbf{y} \]  

Eq. 1

The source distribution, \( \hat{\mathbf{x}} \), is solved with an iterative approach that is both robust and accurate. In addition, array characteristics are extracted from the source definition presentation.
In the study by Brooks and Humphrey, simulations and practical tests were conducted to validate the DAMAS methodology. To begin the validation, a simulation of a simple point source with a small aperture directional array (SADA), which was positioned five feet from the plane that was positioned through a typical model location, was used. Figure 3 illustrates a typical calculation plane grid and array set up. For the point source simulation, the calculation plane (scanning plane) parameters are \( H = W = 50 \text{ in}, \) \( \Delta x = \Delta y = 1 \text{ in}, \) and results in 2601 grid points. With a selected frequency of 10 kHz and beamforming the following parameters are determined, \( B \approx 12 \text{ in}, \) so \( H/B = W/B = 4.17 \) and \( \Delta x/B = 0.083. \) A synthetic point source was the placed in the center of the scanning plane at \( n = 1301. \) This is the result of specifying \( X_{1301} \) such that \( 100 \text{ dB} = 10 \log X_{1301} \) and all other values of \( X \) are set to zero, and then Eq. 1 is solved for \( \hat{Y}. \) With this, the values of \( 10 \log Y_n \) are plotted as a contour. The results were plotted and are provided in Figure 4 for classical beamforming (STD beamforming) and DAMAS for one,
Figure 4 - Synthetic point source simulation results with STD beamforming and DAMAS at 1, 1000, and 5000 iterations. [5]
one thousand, and five thousand iterations. With 5000 iterations, the originally inputted value of 100 dB was recovered to 0.1 dB and the surround levels approximately 40 dB lower. This excludes the adjoining grip points, which were down by 15-20 dB. Levels were acquired by integrating over the spread region. In comparison, at the 1000th iterative step 100.03 dB was recovered and the 100th iterative step was recovered to 99.06 dB. Although the integrated levels are near 100 dB, source spreading occurs. For this application, the 1000th iteration is sufficient for accurate results in both source distribution and level.

A comparison displaying the effect of beamwidth, B, was conducted by Brooks and Humphreys [5]. In Figure 4 (b), beamwidth was reduced by a factor of two, resulting in a coarser $\Delta x/B$ ratio of 0.167 at $f = 20 \text{kHz}$. The contour plot shows similar source identification with a more contracted spread distribution. At 1000 iterations, a more exact solution was achieved; 99.97 dB with adjoining points reduced by 27 dB is achieved.

Beamwidth is reduced even further in Figure 4 (c), such that $\Delta x/B = 0.25$ and $f = 30 \text{kHz}$. It is noted that less iterations are required to obtain a more exact result. A 100 dB peak and adjoin points lesser by 61 dB is achieved at the 1000th iteration. With a decreased beamwidth, even the 100th iteration was comparable to the 5000th iteration when $\Delta x/B = 0.083$ as shown previously. In general, a coarser $\Delta x/B$ ratio required less iterative steps and yielded better results for both source distribution and level for a simple source.

In the same study, a simulation was computed for a more complicated sound source. The synthetic sound source was achieved with the same method as the simple point source mentioned. $X_n$ was set to 100 dB for all $X$ required to form the sound source, which in this
Figure 5 - NASA image sound source with same conditions as Figure 4. [5]
case was the image of the word ‘NASA’. The resulting processed contour plots are illustrated in Figure 5. Figure 5 (A) shows the contour plots for $f = 10 \ kHz$ and $\Delta x/B = 0.083$. Classical beamforming yielded a sound map an almost identical to that of a line source. Although the DAMAS method did not converge even after 30000 iterations, it had identified that the source was more complex than a line source. At $f = 20 \ kHz$ and $\Delta x/B = 0.167$, the image was recognizable before 100 iterations and a prominent image was achieved. Finally, when $\Delta x/B = 0.25$ and $f = 30 \ kHz$ all components of the image were apparent. Total noise rapidly converged to the correct value within 1 dB at 16 iterations and within 0.05 dB at the 100th iteration for all three values of $\Delta x/B$. The major concern for the complicated source was the image convergence, but it was demonstrated that with a coarse $\Delta x/B$, image convergence of a complicated sound source can be achieved.

For both simulations, for simple and complex sources, a coarser $\Delta x/B$ ratio required less iterations to achieve results of the same ‘accuracy’ as a finer $\Delta x/B$ ratio. This observation was even more prominent for complex sources. For $\Delta x/B$ ratios that were too coarse, the plotted images became disrupted. On the other hand, too fine of a $\Delta x/B$ ratio resulted in image spreading. Thus, it was recommended to have a $\Delta x/B$ ratio at or below 0.2 to avoid aliasing problems while remaining coarse enough to maintain both an accurate image and level.

In addition to the simulation verification tests, Brooks and Humphreys outlined experimental applications and re-processed several airframe component noise studies conducted in Langely Research Center’s Quiet Flow Facility (QFF) utilizing the DAMAS methodology [5]. For these applications, DAMAS was not used with an optimum
resolution and scanning plane. All cases fell at or near the accepted range of $0.05 \leq \Delta x/B (\& \Delta y/B) \leq 0.2$. All measurements computed with DAMAS used 1000 iterations. Results were presented in terms of 1/3-octave bands for several array processing methodologies for the sole purpose of direct result comparison to previous studies.

A calibrator source with and without airflow was examined. The calibrator source was composed of an open end of a one inch diameter tube positioned next to the flap edge of an airfoil at an angle-of-attack (AoA) of 16°. The scanning plane parameters used were as follows: $H = W = 12\ in$, $\Delta x = \Delta y = 0.55\ in$ and $B = 12\ in$, which resulted in a resolution of $\Delta x/B = 0.046$. The resulting scanning plane in accordance to the specified parameters resulted in 441 grid points and 1000 iterative steps were used for each frequency band. The 1/3-octave band presentation for $10\log Y$ at $f_{1/3} = 4\ kHz$ was obtained separately by solving for 546 bands and then summing the results. Resulting contour plots are illustrated in Figure 7 and Figure 6.
The results yield more accurate spatial distribution that quantifies both position and strength of aeroacoustic sources. DAMAS results in Figure 6 (b) are of particular interest because, to the knowledge of Brooks and Humphreys, the result may have been the first direct measure of the spatial dispersion of noise resulting from turbulence scatter [5]. The dotted areas in Figure 6 and Figure 7 demonstrate the integration region used to calculate integrated sound levels. The levels from this study were compared to a previous study conducted by Brooks and Humphreys in which the array data was processed using the classical beamforming approach [6]. While the levels were comparable, the image yielded from DAMAS displayed a more accurate and contracted source identification [5].

Brooks and Humphreys noted the edge effects in the DAMAS solutions by the non-negligible amplitudes along the border of the calculation plane. DAMAS measured through beamforming will measure and calculate whatever noise is present at the grid point of the calculation plane, which can be influenced by sources outside of the scanning plane. Edge effects were examined by expanding the calculation plane. This generated almost identical results other than at the edge regions. Thus, the edge effects had negligible impact on the contour plot results and the integrated regions. [5]

Diagonal removal (DR) method was applied to STD beamforming and DAMAS beamforming in Figure 7 under the same conditions as in Figure 6. Even though the DR process modified the Y distribution, the source distribution X and values were almost identical to that of the results without DR. The advantage of DR is removing the autospecta and microphone noise contamination from the software processing. Matrix rank for the solution equations are still maintained [5].
Another test performed in the study by Brooks an Humphreys was the trailing edge and leading edge noise test [5]. A NACA (National Advisory Committee for Aeronautics) 63-216 airfoil, with a 16 in chord and 36 in span, was positioned at an angle-of-attack of -1.2° to the vertical flow. NACA airfoils are airfoils of various shapes developed by the National Advisory Committee for Aeronautics with assigned numbering to identify the aerodynamic and geometrical characteristics of the airfoil [7]. The airfoil has a uniform sharp Trailing Edge (TE) of 0.005 in [5]. To ensure a fully turbulent flow, #90 sized grit was distributed over the first 5% of the Leading Edge (LE). SADA was positioned at $\varnothing = 90^\circ$ with a scanning plane of size $H = W = 50\text{ in}$. Figure 8 and Figure 9 display array output for four 1/3-octave band frequencies with STD processing and DAMAS, respectively. For the 2.15 kHz frequency band, an intense region close to the airfoil TE was noted. As the frequency was increased, the intense region became more concentrated at the TE and shifts toward the LE. The DAMAS results in Figure 9 accurately illustrated the noise source distributions, even the source distributions not apparent with STD processing. For $f_{1/3} = 3.15\text{ kHz}$, $\Delta x = \Delta y = 1.8\text{ in}$ was used. This obtained the resolution of $\Delta x/B = 0.047$. For 1/3-octave band frequencies 8, 12.5 and 20 kHz, $\Delta x = \Delta y = 1\text{ in}$ was used; which results in resolutions of 0.066, 0.083 and 0.083, respectively. It was apparent that TE and LE line sources were well defined with DAMAS. Phantom images at the TE and around the edges of the scanning plane were noted.

Diagonal removal processing was utilized in the results presented in Figure 10 and Figure 11. The DR process produced beamforming contours that differed significantly; however, the source distribution was essentially the same. DR produced cleaner DAMAS results, such that most phantom images were removed from the contour. Thus, the contour
did not display a source where no such source existed. The results produced with the

Figure 8 - Contours for shaded
STD beamforming - TE and LE
noise test [5].

Figure 9 - DAMAS results
corresponding to Figure 8 – TE and LE
noise test [5].
addition of DR are considered to be more correct, due to the reduction of contamination

Figure 10 - Contours for Shaded DR processing - TE and LE noise test [5].

Figure 11 - DAMAS results corresponding to Figure 10– TE and LE noise test [5].
with turbulence buffeting microphone self-noise [5]. To further remove any phantom images, edge effects can be eliminated by expanding the scanning plane beyond the regions of strong sources, in turn the edge amplitude would be reduced and the potential influence on the regions of interest will be diminished.

The DAMAS method was introduced and had been extensively studied and verified through simulation as well as experimental applications. Brooks and Humphreys had effectively accessed the strengths and weakness of the DAMAS technique. With the proper set up of the calculation plane, resolution, and measurement array, the DAMAS method yields accurate results. DAMAS was a radical step forward in array processing, restoring faith in deconvolution methods as a practical method for obtaining NSI results. No additional assumptions are made with the use of DAMAS. This methodology simply extracts array characteristics based on the presentation of the sound definition. The iterative approach obtains concentrated noise source distribution while leaving flexibility in the number of iterations in order to obtain more accurate results depending on the spatial resolution and size of the calculation region in comparison to beamwidth. Brooks and Humphreys proved the DAMAS algorithm to be adept with various aeroacoustic applications. [5]

The release of a study by Dougherty in 2005 expanded upon the existing DAMAS algorithm with the principal objective of overcoming the limitations in the original methodology [8]. DAMAS2 and DAMAS3 were proposed and examined by Dougherty. The original DAMAS algorithm is an iterative non-negative least squares (NNLS) solver that removes side lobes (and phantom images) and generates accurate NSI results. The main challenge of DAMAS is the lengthy processing time and the lack of an explicit
regularization technique to control the amplification of high frequency noise in the reconstruction of the sound field. The extension, DAMAS2, yielded a dramatic decrease in processing time for each iterative step while also having added a regularization by means of a low pass filter. Like DAMAS2, DAMAS3 provided fast iterations while also reducing the compulsory number of iterations. Regularization is obtained in DAMAS3 through a technique partially based on a Wiener filter.

In this study, Dougherty expanded on an example presented in ‘Advanced time-domain beamforming techniques’ in 2004 [9]. Synthetic data was used to quantify results from the various deconvolution beamforming algorithms. The test used a circular 63-channel microphone array with a diameter of 34.4 in [8]. The calculation plane was located 100 in from the array and parallel to the array plane. The results were analyzed over a 1/12-octave band centred at 4 kHz. A synthetic V-shaped source was produced by generating 127 independent random source functions. The individual point source sound waves

![Figure 12 - Source strength distribution](image1.png)

Figure 12 - Source strength distribution $q(\vec{x})$. V-shaped source comprised of 127 source points. Grid points are separated by 0.5” in

![Figure 13 - Delay and sum beamforming results](image2.png)

Figure 13 - Delay and sum beamforming results for the source strength distribution in Figure 12 at 4 kHz [8].
propagate toward the microphones and were coherently summed. This resulted in a source strength distribution as illustrated in Figure 12. The result used a sampling rate of 32000 samples per second with duration of 4 seconds. The data was low pass filtered and then band pass filtered to the 4 kHz 1/3-octave analysis band. It was expected for the V-shape source to be greater than a single point source by a factor of 127 (21.03 dB) since it was composed of 127 independent sources. In reality, the V-shape source was greater by a factor of 95 (19.77 dB) due to the source geometry increased lengths of the propagation paths of the sound waves in some cases. Figure 13 presents the DAS beamforming with diagonal removal [10]. The source was accurately located but source spreading and side lobes were present.

![Figure 13 - DAS beamforming with diagonal removal](image)

Figure 14 - Deconvolution using a Weiner filter with regularization parameter $\gamma = a)$ 0.1, $b)$ 0.001, and $c)$ 0.00001 [8].

Deconvolution with implementation of a Weiner filter was used with regularization parameters, $\gamma$, of 0.1, 0.001, and 0.00001 [8]. The resultant integrated values for the three source reconstructions in Figure 14 are 43.5 dB, 48.93 dB, and 52.42 dB for Figure 14 a, b, and c respectively. These integrated values are not related to the microphone sound pressure level, which inferred the Weiner filter was not suitable for this application.
In this application, Dougherty also implemented the DAMAS2 methodology, and the results are illustrated in Figure 15 [8]. The results show DAMAS2 with and without a regularization method. Figure 15 a) does not implement regularization, while Figure 15 b) used a low pass band filter with a cut-off of 0.5 pixels (0.5 in). Without regularization, the calculation required 12 seconds to accomplish 500 iterations on a laptop computer. The reconstruction of the sound field is satisfactory, the only concern having been some small spots in the source region. The integrated level is 20.32 dB, which was consistent with the levels measured at the array microphones. The computation time of the results and the corresponding integrated value of the results with implementation of a low pass field were the same as that without regularization. Low pass filter results of DAMAS2 produced a small increase in blurring but removed the spots in the source region present in Figure 15 a).

Dougherty concluded DAMAS and its expansions significantly improved the results of array signal processing [8]. DAMAS2 significantly increased calculation speed relative to DAMAS by implementing an FFT processor to reduce time at each iterative
step. DAMAS3 can further improve speed by not only reducing the calculating time of each iteration but also reducing the number of iterations required for convergence. Through Dougherty’s practical examples, it had been proven that extensions of DAMAS improved the results of beamforming for various applications.

NSI is a constantly growing tool with continuously advancing methodologies and techniques. Many studies have been conducted that drive NSI to new heights. With various techniques and algorithms readily available, there exists a method for a vast range of applications. With the advancements in NAH and beamforming, it has become easier to apply NSI to many very different applications with test specific challenges and limitations. Beamforming has become the leader in NSI through its versatility and accuracy. Deconvolution methods contributed significantly to beamforming performance and resulted in a new standard of accuracy and precision in NSI. Today, NSI is a widely accepted tool, but requires further research and development of standard tests procedures and even further advancements in methodologies.

From the above research, deconvolution methods have proven to provide the highest spatial resolution while minimizing side lobes and window effects. Therefore, in the implementation of NSI in this thesis, a deconvolution method has been chosen. Using B&K software, refined beamforming has the highest spatial resolution. Refined beamforming employs the original DAMAS algorithm, which incorporated an iterative NNLS solver. This algorithm was the most accurate and readily available method within the compliment of B&K software and having fast processing capabilities. As such, the goal in using the chosen beamforming methodologies is to have results that are the most accurate and precise of the deconvolution beamforming algorithms.
2.2 Noise Abatement

Noise abatement is a crucial practice within industrial operations containing sensitive receptors within close proximity. Basic abatement principles are utilized in practice to reduce the noise emission of industrial operations to adhere to the strict guidelines/by-laws set by the MOE. These by-laws place full responsibility to those individuals governing the noise emitting operations to ensure that their noise emission impacts adhere to the compliance limits. Depending on the type and severity of the noise pollution issue, a wide range of mitigation options exists to reduce the impacts.

When accessing a noise problem, the application of the noise abatement treatment is paramount in the treatment’s effectiveness. In industrial practices of noise control, a systematic approach is taken as the transfer or path of sound is divided into three major elements: the source, the transmission path, and the receiver [11]. Noise abatement can be applied at any point in the transfer of sound. Modifications can include any of the following:

- Reduction of sound power level of the source
- Reduction of vibration level of the source
- Modification of spectral content of noise
- Modification of wave form of impulsive sound
- Modification of environmental noise climate
- Masking of sound
- Changes of sound exposure as experienced by the recipient

The approach in selecting where to physically apply noise abatement is dependent on the type of application in which the noise abatement is being utilized. Noise control applied at
the receiver(s) location can be cost-effective but is not always convenient. Despite the reduction of sound level perceived by the complainant, not everyone will benefit from the noise control set in place. To prevent large areas from being affected by noise pollution, noise control would have to be applied between the source and the receptor area or directly to the source. Modification to the sound source could be very extensive and in many cases not a feasible solution. Equipment for industrial purposes are specifically designed to complete a certain task and the altering of such equipment could reduce functionality that ultimately cannot be sacrificed. In such cases, noise abatement treatments would be applied in the transfer region between the source and the receiver, with application focused close to the source for the best reduction in overall noise emission; a simple example is a roadway noise barrier.

In Noise Control Principles and Practice by Brüel & Kjær, the three leading methods to reduce noise in a factory/industrial plant setting is to 1) reduce the noise at the source, 2) change to quieter methods of work, 3) and/or prevent propagation [12]. These three approaches are common practices in industrial noise control, however, they are not limited to factory setting applications. The transmission of acoustical energy is fundamentally the same in different environments/settings where noise control is required. The basic principles of sound emission and corresponding preventions includes: preventing the emissions from being emitted at the source, interrupting the transmission path, or preventing the perception by the receiver remains the same.

When modifications to the source and receiver are not practical, enclosures or barrier materials are employed to control the noise emission of the source. Enclosures are insulating structures designed with the purpose of containing the sound field. An enclosure
would block the propagation of sound directly emitting at the source. Barriers are referred to as partial enclosures placed in the path of the sound radiation to block the transmission of sound energy to the receiver. Barriers create an acoustic shadow in which the sound emission from the source is not fully perceived. Low frequency sound will diffract around the barrier, while high frequency sound is better controlled with the use of barriers [11]. In addition to the size of the barrier, the distance from the barrier to the sound source and receptor will also affect the noise reduction.

From the statements provided, it can be concluded that full enclosures are preferred; however, depending on the function of the equipment, a full enclosure is often not be feasible. In such cases, partial enclosures may be employed instead. As stated, enclosures provide a high noise reduction and can be designed to surround the source or to provide an area of reduced noise level at the receiver. The first option is preferred since noise abatement applied near a source will provide noise reduction for all receptors within an audible range of the source.

When employing enclosures near to the source, concern in selecting the barrier material is elevated. The air confined between the source and the enclosure produces a mass-spring system that resonates at certain low frequencies. To reduce this effect, the mass per unit area or the spacing between the enclosure and the source must be increased [11]. Alternatively, if the attenuation at low frequencies is required to be increased by increasing the resonant frequency for a specified enclosure, the mechanical stiffness of the enclosure must be improved. Further, to reduce the amplitude of resonant frequencies, the damping of the material applied will have to be significant. At higher frequencies, absorptive materials provide effective abatement of noise and associated resonances.
It is important to understand the effect(s) of the environment on the spectral data when determining the preferred abatement. In cases where the receptor is close to the source, the high frequency noise is perceived as more annoying than the low frequency content. In the contrary, low frequency noise is perceived as more annoying at distances far from the source [12]. Low frequency sound propagates further than high frequency sound as a result of the characteristics of the atmospheric absorption. Thus, in scenarios where residential receptors are far from the sound source, the abatement of low frequency noise becomes critical in minimizing the noise impact at the receptors.

As stated, while there are systematic approaches to noise abatement, designed abatement can vary greatly from one application to the next. Every instance will have different limitations that need to be met and different noise reduction requirements. The challenge in abatement of industrial sources is adhering to the MOE guidelines without reducing operations. Dependent on the environment and resources available, the preferred noise abatement will be selected for every unique application.

Barriers can be comprised of various types of materials. In acoustics, there are three basic types of acoustic materials: absorbing materials, barrier materials, and damping materials. Absorbing materials are designed to absorb the acoustical energy in porous or fibrous materials which transfers the aerodynamic energy to thermodynamic energy [13]. This transfer of energy to heat occurs within the absorption material itself. Barrier materials are best described by transmission loss. That is, the sound stopping power of the barrier. Barriers are designed to block the transmission of sound through reflection as opposed to the dissipation of acoustical energy with an absorption material. Unlike the previous two materials, damping material is any material applied to a structural member to increase its
damping properties. Damping materials are utilized to dissipate mechanical energy associated with vibration. In common noise control practice, barrier materials are composites comprised of a combination of the acoustic materials described in this section. Most commonly, a barrier and absorption material would be utilized in a composite to reap the benefits of both materials. By gaining the absorbing materials dissipation of acoustical energy and the sound stopping power of the barrier material, the composite will overall perform better than one of the materials alone.

In order to commence the design of a noise abatement treatment, the problem source is first identified and working outwards from the source with modifications or applications of noise abatement as close to the source as possible in the transfer chain to achieve the greatest benefit. Barriers and enclosures are common noise control solutions when the overall sound power level of the source cannot be reduced. With the application of barriers and enclosures, material selection for a noise abatement with good absorption and transmission loss is crucial in providing adequate noise reduction. Noise control is paramount in managing noise emissions of industrial and commercial sources.
III. Theory

3.1 General Acoustics

In order to introduce the theory behind beamforming and holography in acoustics, a basic understanding of acoustic fundamentals is required. Fundamental terminology and theories are covered in this section. Covered fundamentals include sound pressure level, sound power level, sound intensity level, addition and averaging of decibel levels, and relationships between sound pressure, power and intensity. These theories provide a foundation for the understanding of NSI methodologies such as nearfield acoustic holography and beamforming.

The most fundamental concept in acoustics is sound. Sound is a pressure fluctuation that propagates through air (or any median) which results in the excitation of the human ear for the perception of sound. In contrast, noise is characterized as any unwanted sound. Sound that disrupts communication, work, rest, recreation and sleep are considered noise. [14]

Aside from measured sound level, frequency (f) of propagating acoustic energy is a characteristic of the periodic sound wave. The relationship between frequency, sound wavelength, and speed of sound is expressed in (3.1-1)[14][14][14][14][15][14].

\[ f = \frac{c}{\lambda} \]  

(3.1-1)

Sound level is most commonly measured in units of decibels (dB), which is a logarithm representation of the strength of a sound unit relative to a reference level. Sound of an object is most often quantified as either a sound pressure level (SPL) or a sound
power level ($L_w$). SPL is acoustic sound pressure ($P$) in relation to a reference sound pressure ($P_o$) expressed in decibels. This relation is given in equation (3.1-2), with the variable $L_p$ being sound pressure level.

$$L_p = 20 \log \left( \frac{P}{P_o} \right)$$  \hspace{1cm} (3.1-2)

Sound pressure level is a characteristic of the source in the environment in which the measurement was acquired. In contrast, sound power level is independent of the measurement environment. Sound power level is solely a characteristic of the sound source. Measured sound pressure level will diminish with distance and with sound propagation due to the effects of the environment, while sound power level remains the same no matter the distance or the environment the source is exposed to [14]. The relationship of sound pressure level and distance is expressed in the following equation:

$$L_{p_2} = L_{p_1} - 20 \log \left( \frac{r_2}{r_1} \right)$$  \hspace{1cm} (3.1-3)

Sound power level is computed from a sound power ($W$) over a reference sound power ($W_o$) expressed in decibels. The sound power level formula and its relationship to sound pressure level are expressed below:

$$L_w = 20 \log \left( \frac{W}{W_o} \right)$$  \hspace{1cm} (3.1-4)

$$L_w = L_p + 20 \log (r) + 11 - DI_\theta$$  \hspace{1cm} (3.1-5)

Equation (3.1-5) introduces directivity index ($DI_\theta$) as a parameter in the conversion to sound power level. Directivity index is a correction factor used to account for radiation of the source as well as environmental absorption and reflections in the propagation of
sound. In a perfect example, a point source spherically radiates sound with sound pressure level reducing by 6 dB for every doubling of distance [14]. This is not the case in real world applications, impact from environmental factors and directivity of the source prevent uniform radiation of sound.

With sound pressure level and sound power level being critical parameters in validation of noise abatement, the perception of the variation in these levels was paramount.

Table 1 – Perceived loudness in relation to change in sound level. [14]

<table>
<thead>
<tr>
<th>Change in Sound Level (dB)</th>
<th>Change in Perceived Loudness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>Just perceptible</td>
</tr>
<tr>
<td>5</td>
<td>Noticeable difference</td>
</tr>
<tr>
<td>10</td>
<td>Twice (or 1/2) as loud</td>
</tr>
<tr>
<td>15</td>
<td>Large change</td>
</tr>
<tr>
<td>20</td>
<td>Four times (or 1/4) as loud</td>
</tr>
</tbody>
</table>

Sound is produced by a sound source with a sound power (W) through a transfer of energy from the source to the air molecules. The energy is then propagated outwards through the transfer of energy to outlying molecules. This energy is transferred at a rate through a particular area, which is quantified as sound intensity (I). It is important to note that sound intensity is a vector quantity. Sound intensity level is a decibel quantity of sound intensity above a reference intensity. Sound intensity, and sound pressure alike, can be measured with the proper instrumentation while sound power is calculated from sound intensity or sound pressure measurements. Sound intensity is related to sound power by an integration of sound intensity over a specified area. For a spherically radiating sound source, the relationship of sound intensity to sound power is expressed as follows:
Sound intensity is sound power per unit of area. This concept is key in the calculation of sound power level utilized in Brüel & Kjær software packages employed in this study. Sound intensity level (\(L_I\)) is the fundamental characteristic used in the results that are presented in this study.

Sound levels expressed in decibels follows logarithmic operators when simple statistics are to be calculated. Logarithmic addition and logarithmic averaging are most utilized with dealing with multiple sound sources or multiple measurements of a single sound source. The formulae for both operations are presented below:

\[
L_{PT} = 10 \log \left[ \sum_{i=1}^{N} 10^{\frac{L_{PI}}{10}} \right] \quad (3.1-7)
\]

\[
L_{pavg} = 10 \log \left[ \frac{1}{N} \sum_{i=1}^{N} 10^{\frac{L_{PI}}{10}} \right] \quad (3.1-8)
\]

The fundamentals presented in this section will be the foundation of NSI algorithms and manipulation of the collected sound data to acquire the results presented in this study.

3.2 Nearfield Acoustic Holography

Holography is a widely utilized concept employed in several fields such as optics and acoustics. Early acoustic holography copied of optical holography systems. In the most basic terms, acoustic holography is the reconstruction of a three dimensional acoustic wave field from a two dimensional recording on a hologram plane offset and parallel to the source plane. In an article by Maynard, Williams, and Lee it was stated, “that if a picture is worth 1000 words, then a hologram is worth \(1000^{3/2}\), or approximately 32000 words”
This statement is completely accurate in regards to the digital processing of a hologram; if a hologram is measured to have 1000 digital ‘words’ of data a cubical, a three dimensional reconstruction would then have 32000 digital words of data. The limitation of the reconstruction is solely based on the computation time. In regards to the applications, in nearfield acoustic holography, a two dimensional sound pressure level measurement can be used in the reconstruction of a three dimensional sound pressure level field, particle velocity field, acoustic vector intensity field, surface velocity and intensity of a vibrating source, etc.

In outlining the theory of NAH, correlation is made to properties of a vibrating plate with properties of radiated sound field power, far field directivity pattern, the vector intensity field, etc. Measurements of vibrator displacement, particle velocity, or sound pressure are insufficient in the determination of the energy delivery to the sound field from the vibrating plate. The key to understanding the radiation of sound from the vibrating plate is from the acoustic intensity vector $S(r)$, presented below in Equation (3.2-1). To begin, for one frequency, intensity is the product of the in-phase components of the pressure amplitude, $P$, and the velocity amplitude, $v_o$:

$$S(r) = \frac{1}{2} P(r)v_o(r) \cos \theta$$  \hspace{1cm} (3.2-1)

Equation (3.2-1) specifies that at each point in space both the rate and direction of the acoustic energy flow. There exist techniques such as the two microphone intensity method to determine acoustic vector intensity, but taking a single measurement for every point on a hologram plane is impractical. With NAH, the mapping of three components of vector...
intensity for a large number of points is within its capacity. The basic features of NAH are outlined below as follows:

1) A single measurement over a two dimensional surface (a planar microphone array) is all that is required;

2) Results can be produced in minutes;

3) Measurements cover a large area (dependant on the microphone array);

4) Measurements have high spatial resolution;

5) NAH is able to display the sound pressure field from the source to far field, particle velocity field from the source to far field, modal structure of a vibrating surface, vector intensity field, far field radiation pattern, and total radiated power.

In holography, a measurement of a two dimensional surface is used to calculate a three dimensional wave field, ψ. When creating a wave field, ψ(r, t), it is assumed to satisfy the homogeneous wave equation:

\[ \nabla^2 \psi - \frac{1}{c^2} \frac{\partial^2 \psi}{\partial t^2} = 0 \]  \hspace{1cm} (3.2-2)

Furthermore, it is assumed that there is a surface, S, enclosing the three dimensional region of interest for a known Green’s function, \( G(r|r_s) \), which satisfies the homogeneous Helmholtz equations for \( r \) inside of \( S \) and vanishing for \( r = r_s \). Secondly, there is a hologram surface, \( H \), that is coincidence with \( S \) or has a level surface parallel to \( S \) for which \( \psi(\mathbf{r}_H, t) \) is measurable for all \( \mathbf{r}_H \) on \( H \) for all time, \( t \). If required assumptions are met, then \( \psi(\mathbf{r}, t) \) for \( \mathbf{r} \) within \( S \) can be determined from \( \psi(\mathbf{r}_H, t) \) with \( \mathbf{r}_H \) on \( H \).
The first step in determining $\psi(r, t)$ from $\psi(r_H, t)$ is to perform a Fourier transform in the time domain.

$$\tilde{\psi}(r, \omega) = \int_{-\infty}^{\infty} \psi(r, t) e^{i\omega t} dt$$  \hspace{1cm} (3.2-3)$$

$$\tilde{\psi}(r_H, \omega) = \int_{-\infty}^{\infty} \psi(r_H, t) e^{i\omega t} dt$$ \hspace{1cm} (3.2-4)

The denotation, $\sim$, represents a complex field that has an amplitude and phase which is dependent upon $r$. The wave equation then becomes the Helmholtz equation.

$$\nabla^2 \tilde{\psi}(r, \omega) + k^2 \tilde{\psi}(r, \omega) = 0$$ \hspace{1cm} (3.2-5)

It is important to note that previously $\tilde{\psi}(r_s, t)$ was required to be measured for all time, that is, $-\infty < t < \infty$. However, in this expression $\tilde{\psi}(r_s, t)$ can be measured for a finite time duration, $T$, if $\tilde{\psi}(r_s, t)$ is known to be periodic with a period equal to $T$. For noise sources there exists a reasonable time $T$ which can be used in most cases. Caution is advised when selecting $T$ for if it is too large there may be an exceedance in the manageable amount of data.

The wave field $\psi(r_H, t)$ is sampled at $N$ discrete points in time $t_n = t_H + \frac{nT}{N}$. It is assumed that the sampling is at the Nyquist rate to remove aliasing. Equation (3.2-3) then becomes:
\[ \bar{\psi}(r_H, \omega_m) \approx e^{i\omega_m t_H} \left( \sum_{n=0}^{N-1} \psi(r_H, t_n)e^{i2\pi nm/N} \right) \frac{T}{N} \]  

(3.2-6)

where \( \omega_m = \frac{2\pi m}{T} \) and \( m \) are a non-negative integer less than \( N/2 \). This summation can be accomplished with a Fast Fourier transform (FFT) computer algorithm. For these sources operating at a set of frequencies \( \omega_m \), the expression presented above in (3.2-6) is exact.

In the spatial analysis, it is considered that \( \omega \) is a fixed value such that the wave number \( k = \omega/c \) and a wavelength \( \lambda = 2\pi c/\omega \). The spatial analysis problem is now to find \( \bar{\psi}(r) \) which satisfies the Helmholtz equation below.

\[ \nabla^2 \bar{\psi}(r) + k^2 \bar{\psi}(r) = 0 \]  

(3.2-7)

This equation is true for \( r \) within a three dimensional region of interest.

In the next step the wave field is to be processed in a spatial domain. Since it is assumed that the Green’s function, \( G(r|r_s) \), is required to satisfy the homogeneous Dirichlet condition on the surface \( S \) is known, then the solution \( \bar{\psi}(r) \) for equation (3.2-7) can be found with a surface integration:

\[ \bar{\psi}(r) = -\frac{1}{4\pi} \int \! \int \bar{\psi}(r_s) \frac{\partial G}{\partial n}(r|r_s)d^2r_s \]  

(3.2-8)

where \( \partial G/\partial n \) is the derivative of \( G \) with respect to \( r_s \). If \( H \) is the same as the surface \( S \) where \( \bar{\psi}(r_H) \) is measured then the calculation is complete; however, if \( H \) lies within \( S \) then the calculation proceeds as follows. Three spatial coordinates are denoted by \( \xi_1, \xi_2, \) and \( \xi_3 \); with the level surface \( S \) given by \( \xi_3 = \xi_3^S \). The hologram plane \( H \) which lies inside \( S \) is given by \( \xi_3 = \xi_3^H \), such that \( \xi_3^H > \xi_3^S \). Thus, in terms of \( \xi_1, \xi_2, \) and \( \xi_3 \) Equation (3.2-8) becomes

40
\[\tilde{\psi}(\xi_1, \xi_2, \xi_3) = -\frac{1}{4\pi} \int \int \tilde{\psi}(\xi'_1, \xi'_2, \xi'_3)\]
\[\times \left( \frac{\partial G}{\partial \eta} (\xi_1 - \xi'_1, \xi_2 - \xi'_2, \eta) \right)_{\eta = \xi_3 - \xi'_3} d\xi'_1 d\xi'_2 \]  
\text{(3.2-9)}

and evaluated when \(\xi_3 = \xi_3^H\) Equation (3.2-8) then becomes:

\[\tilde{\psi}(\xi_1, \xi_2, \xi_3^H) = \int \int \tilde{\psi}(\xi'_1, \xi'_2, \xi'_3^S) G_{HS}(\xi_1 - \xi'_1, \xi_2 - \xi'_2) d\xi'_1 d\xi'_2 \]  
\text{(3.2-10)}

Where \(G_{HS}(\alpha, \beta) = -\frac{1}{4\pi} \frac{\partial G}{\partial \eta} (\alpha, \beta, \eta) \mid_{\eta = \xi_3^H - \xi_3^S}.\)

Simplification to Equation (3.2-10) is achieved by Fourier transforms. Denote a two dimensional spatial Fourier transform by \(\hat{\cdot}\) and it’s inverse by \(\mathcal{F}^{-1}\). Equation (3.2-10) and the convolution theorem results in the following relations presented below.

\[\hat{\psi}(\xi_3^H) = \hat{\psi}(\xi_3^S) \hat{G}_{HS} \]  
\text{(3.2-11)}

Solving equation (3.2-11) for \(\tilde{\psi}(\xi_1, \xi_2, \xi_3^S)\) results in

\[\tilde{\psi}(\xi_1, \xi_2, \xi_3^S) = \mathcal{F}^{-1} \left[ \hat{\psi}(\xi_3^H) \hat{G}_{HS}^{-1} \right] \]  
\text{(3.2-12)}

After \(\tilde{\psi}(\xi_1, \xi_2, \xi_3^S)\) has been determined, Equation (3.2-9) is then used to reconstruct \(\tilde{\psi}(\xi_1, \xi_2, \xi_3)\) over the entire three dimensional region inside of \(S\).

Conventionally in holography, holograms are recorded and measured on a plane surface. Processing of planar hologram data is easiest from a computational view. The Cartesian system with rectangular coordinates \((x, y, z)\) are utilized for plane holography. In terms of rectangular coordinates, the surface \(S\) is defined as the infinite plane at \(z = z_s\)
and the infinite hemisphere enclosing the $z > z_s$ half-space. Maintaining the assumption that the source is planar, such as a vibrating plate, aids in the understanding of the methodology.

It is desired to rework equation (3.2-7) to relate $\tilde{\psi}(x, y, z)$ to $\tilde{\psi}(x, y, z_s)$. In order to do so, a Green’s function, which satisfies the homogeneous Dirichlet boundary condition on $z_s$, is required. Green’s function is given by:

$$G(x, y, z | x', y', z') = \frac{\exp[ik \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}]}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}}$$

(3.2-13)

$$= \frac{\exp[ik \sqrt{(x-x')^2 + (y-y')^2 + (z+z' - 2z_s)^2}]}{\sqrt{(x-x')^2 + (y-y')^2 + (z+z' - 2z_s)^2}}$$

It is important to note that Equation (3.2-13) is not the free-space Green’s function that contains one single one term in the form $\exp(ikR)/R$. At $z' = z_s$, the normal derivative $(\partial / \partial z')$ is

$$-4\pi G'(x - x', y - y', z - z_s) \equiv \frac{\partial G}{\partial \eta}(x, y, z | x', y', z_s)$$

$$= -\frac{2\alpha}{\partial \alpha}$$

(3.2-14)

$$\times \left( \frac{\exp[ik \sqrt{(x-x')^2 + (y-y')^2 + \alpha^2}]}{\sqrt{(x-x')^2 + (y-y')^2 + \alpha^2}} \right)_{\alpha = (z-z_s)}$$

Thus, Equation (3.2-8) becomes
\[
\tilde{\psi}(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\psi}(x', y', z_s) G'(x - x', y - y', z - z_s) \, dx' \, dy' \tag{3.2-15}
\]

Expression (3.2-15) is not to be mistaken for an approximation of the Green’s theorem with one of the free-space Green’s function terms dropped.

Hologram data is not recorded at the source \((z = z_s)\) but rather on a defined hologram plane, \((z = z_H)\), that is both above and parallel to the source plane \(S (z_H > z_s)\).

The next step is to evaluate Equation (3.2-15) at \(z = z_H\).

\[
\tilde{\psi}(x, y, z_H) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\psi}(x', y', z_s) G'(x - x', y - y', z_H - z_s) \, dx' \, dy' \tag{3.2-16}
\]

In the expression above, \(\tilde{\psi}(x, y, z_H)\) is the hologram data recorded on the hologram plane.

The relation between \(\tilde{\psi}(x, y, z_H)\) and \(\tilde{\psi}(x, y, z_s)\) can be determined using the convolution theorem. The Fourier transform of \(\tilde{\psi}(x, y, z_H)\) is as follows:

\[
\tilde{\psi}(k_x, k_y, z_H) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\psi}(x, y, z_H) e^{-i(k_x x + k_y y)} \, dx \, dy \tag{3.2-17}
\]

With the convolution theorem Equation (3.2-15) can be rewritten as

\[
\tilde{\psi}(x, y, z) = \mathcal{F}^{-1} \left[ \tilde{\psi}(k_x, k_y, z_s) \mathcal{G}'(k_x, k_y, z - z_s) \right] \tag{3.2-18}
\]

and Equation (3.2-16) can be expressed as

\[
\tilde{\psi}(x, y, z_H) = \tilde{\psi}(k_x, k_y, z_s) \mathcal{G}'(k_x, k_y, z_H - z_s) \tag{3.2-19}
\]

Using equation (3.2-18) to solve Equation (3.2-19) for \(\tilde{\psi}(k_x, k_y, z_s)\) yields
\[ \tilde{\psi}(x, y, z) = \mathcal{F}^{-1} \left[ \tilde{\psi}(k_x, k_y, z_H) \left( \frac{G'(k_x, k_y, z - z_S)}{G'(k_x, k_y, z_H - z_S)} \right) \right] \] (3.2-20)

This resulting expression yields the holographic reconstruction of a three dimensional field \( \tilde{\psi}(x, y, z) \) in terms of the recorded hologram data \( \tilde{\psi}(x, y, z_H) \).

The outlined theorem presents a simple approach for a holography. Plane holography highlights the key points of the methodology. To sum up, a measurement is taken at a hologram plane that is related back to the source surface plane through wave propagation modelling which involves Fourier transforms as well as the convolution theorem. With this methodology, it is possible to reconstruct a three dimensional wave field from a two dimensional hologram measurement. This is the premise of nearfield acoustic holography [15].

### 3.3 Beamforming

#### 3.3.1 Delay and Sum Beamforming

Delay and Sum beamforming is the oldest and the most simple beamforming methodology, that is still widely used today [16]. The premise of DAS beamforming is quite simple. For a propagating waveform, a time delay is applied to each signal in order to align the signals in the time domain and the signals are subsequently summed together. The time delay, \( \Delta_T \), reinforces that the signals are directly related to the length of time it takes for the sound source to propagate to each transducer contained within the microphone array. This delay in time and propagation direction are the means to determining the origin of the test source. \( s(t) \) is the signal emitted from a source located at point \( \hat{x}^0 \). The distance
from the centre of the array to the test source is represented by \( \vec{x}^0 \). The summation of the emitted signals results in the wave field, \( f(\vec{x}, t) \), as measured by the sensors.

Consider an array comprised of \( M \) sensors (microphones) located at distance, \( \vec{x}_m \), from the source, where \( m = 0, ..., M - 1 \). The phase centre of the array is defined as the vector quantity \( \sum \vec{x}_m \). The origin is selected to be coincidence with the phase centre; thus,

\[
\sum_{m=0}^{M-1} \vec{x}_m = \vec{0} \quad (3.3-1)
\]

a waveform measured by the \( m^{th} \) sensor is given by \( y_m(t) = f(\vec{x}_m, t) \). Samples of the wavefield are taken at each microphone sensor on the array. DAS beamforming applies a delay and an amplitude weighting, \( w_m \), to each output for each of the sensor. The newly resulting signals are then summed to yield the beamformer’s output. The DAS beamformer output signal, \( z(t) \), is provided below in Equation (3.3-2).

\[
z(t) \equiv \sum_{m=0}^{M-1} w_m y_m(t - \Delta_m) \quad (3.3-2)
\]

The weighting factor is sometimes referred to as the array’s shading or taper. This factor enhances the beam’s shape and reduces side lobe levels. The delays are adjusted to focus the beamformer on waves propagating from a specified direction, \( \xi^o \), or a particular point, \( \vec{x}^0 \).

Algorithms vary in accordance to whether the array is located in the nearfield or the far field. Nearfield wave propagation direction varies between sensors. In the far field this is not the case, as the direction of the propagation is approximately equal among all of the sensors. This creates difficulty for far field calculations. For the far field, the direction
of propagation can be determined but not the range. In the case of the nearfield, with all of
the propagation directions leading to a common source, the range and direction can be
extracted.

In order to describe beamforming in simplistic terms, the DAS beamformer will be
described for plane wave propagation. DAS beamforming gazes in a specified direction to
focus on a sound source that is propagating from the source. By adjusting the delays, the
direction of focus is altered with the goal of coinciding with the direction of the sound’s
propagation. This is referred to as phase steering since the steering is performed
electronically. It is worth noting that an assumption is made that \( \zeta \) is a unit vector negative
to the direction of focus. When a plane waveform, \( s(t) \), is radiated from a farfield source
the wavefield within the array’s aperture is expressed by:

\[
f(\hat{x}, t) = s(t - \vec{d}^o \cdot \hat{x})
\]

With a slowness vector \( \vec{d}^o = \zeta^o / c \).

The \( m^{th} \) sensor’s purpose is to spatially sample the wavefield which
yields \( y_m(t) = s(t - \vec{d}^o \cdot \hat{x}) \). The DAS output then becomes

\[
z(t) = \sum_{m=0}^{M-1} w_m s(t - \Delta_m - \vec{d}^o \cdot \hat{x}_m)
\]

With this expression, phase steering is possible through the adjustments of the delays. The
delay is expressed as follows.
\[
\Delta_m = \frac{-\zeta \cdot \hat{x}_m}{c} = -\hat{d} \cdot \hat{x}_m \quad (3.3-5)
\]

By adjusting the assumed direction of propagation, \( \vec{\zeta} \), the beamformer is steered to focus in a specified direction. With this information, the beamformer signal for a plane wave with propagation direction \( \vec{\zeta}^0 \) becomes

\[
z(t) = \sum_{m=0}^{M-1} w_m s(t + (\vec{a} - \vec{d}^0) \cdot \hat{x}_m) \quad (3.3-6)
\]

It is important to note that if the wrong propagation direction is selected, that is, \( \vec{a} \neq \vec{a}^0 \), a degraded output signal will result. This can occur for two reasons. The first being simply that the incorrect propagation direction is selected. Second, the wrong speed of the propagation is used. With the knowledge of one of these values, the other can be calculated with the wavenumber searching for the maximum output energy. Without the speed of propagation or the direction of propagation, the proper amplitude is not obtainable unless a three-dimensional array is employed.

Traditionally, linear time-invariant systems are characterized by examining their outputs for sinusoidal inputs. The system’s frequency response is determined by performing this analysis over all relevant frequencies. To accomplish this for the DAS beamformer, the array pattern is required. The array pattern is the response of the beamformer to a monochromatic plane wave. The directivity pattern is also determined from the array pattern. In order to determine the array pattern, it is assumed that a monochromatic plane wave with frequency \( \omega^0 \) is propagating with a slowness vector \( \vec{d}^0 \). The wavefield is then given by
\[ f(\vec{x}, t) = s(t - \vec{a} \cdot \vec{x}) = \exp[j \omega^o (t - \vec{a} \cdot \vec{x})] \]  
(3.3-7)

A DAS beamformer with a monochromatic wave as the test signal yields an output of

\[ z(t) = W(\omega^o \vec{a} - \vec{k}^o) e^{j \omega o t} \]  
(3.3-8)

Where \( \vec{k}^o = \omega^o \vec{a}^o = (\omega^o / c) \vec{\xi}^o \) and \( W(\cdot) \) represents the Fourier Transform of the sensor weights.

\[ W(\vec{k}) = \sum_{m=0}^{M-1} w_m \exp (j \vec{k} \cdot \vec{x}_m) \]  
(3.3-9)

\( W(\vec{k}) \) represents the array pattern since \( W(\omega^o \vec{a} - \vec{k}^o) \) determines the amplitude and phase of the beamformed signal when the wavefield consists of a single plane wave. With the inverse space-time Fourier Transform used to express an arbitrary wave field, the DAS beamformer output can then be expressed in terms of the array pattern.

\[ z(t) = \frac{1}{(2\pi)^4} \iint_{-\infty}^{\infty} F(\vec{k}, \omega) W(\omega \vec{a} - \vec{k}) \exp(j \omega t) \, d\vec{k} d\omega \]  
(3.3-10)

An array output that is dependant on time as well as space is desirable for NSI. An output signal of a spatiotemporal filter is a function of both time and space, but the beamformer output \( z(t) \) is not. Thus, a relation of \( z(\vec{x}, t) \) is related to the beamformers output by

\[ z(\vec{x}, t) = \iint h(\vec{x}, \tau) f(\vec{x} - \vec{x}, t - \tau) \, d\vec{x} d\tau \]  
(3.3-11)

In the frequency domain, the output equals the inverse Fourier Transform of the product between the wave number-frequency spectra of \( h(\vec{x}, t) \) and \( f(\vec{x}, t) \).
\[ z(\vec{x}, t) = \frac{1}{(2\pi)^4} \int \int H(\vec{k}, \omega)F(\vec{k}, \omega)e^{j(\omega t - \vec{k} \cdot \vec{x})} \, d\vec{k} \, d\omega \]  

(3.3-12)

And at \( \vec{x} = \vec{0} \), Equation (3.3-12) becomes

\[ z(t) = \frac{1}{(2\pi)^4} \int \int H(\vec{k}, \omega)F(\vec{k}, \omega)e^{j\omega t} \, d\vec{k} \, d\omega \]  

(3.3-13)

The DAS beamformer output for a wave field of a monochromatic plane wave, \( \exp\left(j(\omega^0 \Delta_m + \vec{k}^o \cdot \vec{x})\right) \), becomes

\[ z(t) = \sum_{m=0}^{M-1} w_m \exp\left(-j(\omega^o \Delta_m + \vec{k}^o \cdot \vec{x}_m)\right) \exp(j\omega^o t) \]  

(3.3-14)

Comparing equation (3.3-14) to (3.3-13), the term enclosed in the parentheses is identified to be \( H(\vec{k}^o, \omega^o) \); thus, the wavenumber-frequency response for the DAS beamformer is expressed as

\[ H(\vec{k}, \omega) = \sum_{m=0}^{M-1} [w_m \exp(-j\omega \Delta_m)]\exp(-j\vec{k} \cdot \vec{x}_m) \]  

(3.3-15)

The wavenumber-frequency response will summarize the effect of sensor delays and shading on and array’s spatiotemporal filtering properties. The array pattern becomes the primary quantity used in the evaluation of both the array and algorithm designs. To do so, the array pattern is used in two different conceptual ways. Beam pattern is the analysis of the output distribution by signals different from the one in the focused direction [16]. This parameter employs a fixed slowness vector. The second parameter is the steered response. Steered response reveals how the array’s output varies with a wave field’s fixed propagation parameters. For DAS, these parameters are extracted from the array pattern.
is assumed that $\alpha$ represents frequency and propagation direction and the wave field’s propagation parameters are represented by $\omega^o$ and $\vec{k}$.

Array Pattern: $W(\vec{k}) = \sum_{m=0}^{M-1} w_m \exp(j\vec{k} \cdot \vec{x}_m)$

Wavenumber-frequency response: $H(\vec{k}, \omega) = W(\omega \alpha - \vec{k})$

Beam pattern: $W(\omega^o \alpha - \vec{k}^o)$ for fixed $\alpha$

Steered Response: $W(\omega^o \alpha - \vec{k}^o)$ for fixed $\omega^o, \vec{k}^o$

### 3.3.2 Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS)

A deconvolution approach to beamforming substantially increases the spatial resolution of both the results and accuracy of the beamformer’s output. With the introduction of the DAMAS technique, faith was re-established in deconvolution approaches. This was due to the superior results yielded by the DAMAS method in comparison to traditional beamforming methodology.

The first step in the DAMAS technique is to beamform over the source region utilizing traditional methods [5]. Processing begins with the computation of the cross-spectral matrix for each test case data. The original data is processed with a FFT in order to output each element in the cross-spectral matrix. Pressure transform pairs $P_m(f, t)$ and $P_{m'}(f, t)$ are formed from the pressure time recordings $p_m(t)$ and $p_{m'}(t)$, respectively. The elements in the cross-spectral matrix are given by
\[ G_{mm'}(f) = \frac{2}{K w_0 T} \sum_{k=1}^{K} [P^*_mk(f,T)P_{m'k}(f,T)] \]  

(3.3-16)

The full matrix for \( m_o \) microphones is expressed as

\[
\hat{G} = \begin{bmatrix}
G_{11} & \cdots & G_{1m_o} \\
\vdots & \ddots & \vdots \\
G_{m_o1} & \cdots & G_{m_o m_o}
\end{bmatrix}
\]

(3.3-17)

The purpose of the cross-spectral matrix is to steer the beamformer to the chosen noise source location. The steering vector, \( \hat{e} \), is expressed as

\[ \hat{e} = \text{col} \left[ e_1, e_2, \ldots, e_{m_o} \right] \]

(3.3-18)

The components of the steering vector for each microphone is given by

\[ e_m = \frac{a_m r_m}{r_c} \exp(j2\pi f \tau_m) \]

(3.3-19)

Where \( \tau_m \) is the time of signal propagation from point \( n \) on the source plane to microphone \( m \). For standard (STD) beamforming the output power spectrum is as follows:

\[ Y(\hat{e}) = \frac{\hat{e}^T \hat{G} \hat{e}}{\left( m_o \right)^2} \]

(3.3-20)

T in equation (3.3-20) denotes the complex transpose of the matrix.

Shading is used to modify the output beampattern of the beamformer. The shaded steered response of the beamformer is given by

\[ Y(\hat{\epsilon}) = \frac{\hat{\epsilon}^T \hat{W} \hat{G} \hat{W}^T \epsilon}{\left( \sum_{m=1}^{m_o} w_m \right)^2} \]

(3.3-21)

In this expression \( w_m \) is the shading value corresponding to microphone \( m \).
Diagonal Removal (DR) is a modification to the expression used to improve the dynamic range of the array results exhibiting a poor signal-to-noise ratio. DR is applied to the cross-spectral matrix $\hat{G}$, which results in the following output power spectrum displayed in Equation (3.3-22).

$$Y(\hat{\theta}) = \frac{\hat{\theta}^T \hat{G}_{\text{diag}=0} \hat{\theta}}{m_o^2 - m_o} \quad (3.3-22)$$

It is important to note that much attention is to be taken when undertaking in the physical interpretation of the array response map results.

The shaded version of the DR modification of $\hat{Y}(\hat{\theta})$ is expressed as

$$Y(\hat{\theta}) = \frac{\hat{\theta}^T \hat{W} \hat{G}_{\text{diag}=0} \hat{W}^T \hat{\theta}}{\left(\sum_{m=1}^{m_o} \omega_m\right)^2 - \left(\sum_{m=1}^{m_o} \omega_m\right)} \quad (3.3-23)$$

It is common in the studying of aeroacoustic sources of noise using arrays to determine the array response with Equations (3.3-20)-(3.3-23). These expressions produce source maps which reflect the array beamforming pattern characteristic equal to the measured source distribution. To acquire a clear representation of the source distribution, it would be necessary that the array characteristics and source distribution be separated.

Methodology in the DAMAS technique is capable of extracting the source distribution from the beamforming array characteristics. To successfully separate the array characteristics from the source distribution, the following must be followed. First, the pressure transform, $P_m$, of microphone $m$ in Equation (3.3-16) is related to a source located at the position $n$ on the source field. This is pressure transform relation, $P_{m;n}$, is expressed in Equation (3.3-24).
\[ P_{m:n} = Q_n e^{-1}_{m:n} \]  

(3.3-24)

In this expression, \( Q_n \) represents the pressure transform that \( P_{m:n} \) would be if the flow correction and shear layer refraction did not affect the transmission of the noise from the source to the receiver. The following is the product of pressure transforms.

\[ P_{m:n}^* P_{m':n} = Q_n^* Q_n (e^{-1}_{m:n})^* e^{-1}_{m':n} \]  

(3.3-25)

This expression is subbed into Equation (3.3-16) to acquire a cross-spectral matrix for a single source located at \( n \).

\[ \mathcal{G}_{n_{mod}} = X_n \begin{bmatrix} (e_1^{-1})^* e_1^{-1} & \cdots & (e_1^{-1})^* e_{m_o}^{-1} \\ (e_2^{-1})^* e_2^{-1} & \ddots & \vdots \\ \vdots & \ddots & (e_{m_o}^{-1})^* e_{m_o}^{-1} \end{bmatrix} \]  

(3.3-26)

The term, \( X_n \), is the mean square pressure per bandwidth at each microphone \( m \). For the continuation of the method, it is assumed there are \( N \) number of independent sources at different positions. The total cross-spectral matrix then becomes

\[ \mathcal{G}_{mod} = \sum_{n} \mathcal{G}_{n_{mod}} \]  

(3.3-27)

This is then substituted into Equation (3.3-20) and becomes:

\[ Y_{n_{mod}}(\hat{\theta}) = \left[ \frac{\hat{\theta}^T \mathcal{G}_{mod} \hat{\theta}}{(m_o)^2} \right]_n \]  

(3.3-28)

\[ Y_{n_{mod}}(\hat{\theta}) = \sum_{n'} \frac{\hat{\theta}_n^T \mathcal{G}_{n'}}{m_o^2} X_{n'} \]  

(3.3-29)

Where the bracketed term is that of Equation (3.3-26). Equation (3.3-29) simplifies to:

\[ Y_{n_{mod}}(\hat{\theta}) = \hat{\mathbf{A}} X_n \]  

(3.3-30)

The components of \( \hat{\mathbf{A}} \) are expressed as:
\[ A_{nn'} = \frac{\hat{e}_n^T \left[ \hat{\beta}_0 \right] \hat{e}_n}{(m_o)^2} \]  

(3.3-31)

Equating \( Y_{mod}(\hat{\theta}) \) with the processed \( Y(\hat{\theta}) \) from measured data, we are given:

\[ \hat{A} \hat{X} = \hat{Y} \]  

(3.3-32)

The source distribution \( \hat{X} \) can be applied for shaded outputs as well. For diagonal removal modification and the shaded DR beamforming the \( \hat{A} \) matrix becomes:

\[ A_{nn'} = \frac{\hat{e}_n^T \left( \left[ \hat{\beta}_o \right] \right)_{diag=0} \hat{e}_n}{m_0^2 - m_o^2} \]  

(3.3-33)

\[ A_{nn'} = \frac{\hat{e}_n^T \hat{\mathcal{W}} \left( \left[ \hat{\beta}_o \right] \right)_{diag=0} \hat{\mathcal{W}}^T \hat{e}_n}{\left( \sum_{m=1}^{m_o} w_m \right)^2 - \left( \sum_{m=1}^{m_o} w_m \right)} \]  

(3.3-34)

The Equation (3.3-32) is a system of linear equations relating a spatial field of point locations with beamformed output responses, \( Y_n \), to equivalent source distribution at some point. This matrix relation is used to dissociate the array characteristics from the source distribution.

If \( \hat{A} \) were non-singular, the solution would simply become \( \hat{X} = \hat{A}^{-1} \hat{Y} \). Since this is not the case other techniques are employed. The best results were obtained with an iterative method where a physically-necessary positivity constraint on the \( X \) components could be applied smoothly in the iteration [5]. A single linear equation component of Equation (3.3-32) is expressed as

\[ A_{n_1}X_1 + A_{n_2}X_2 + \cdots + A_{nn}X_n + \cdots + A_{nn}X_N = Y_n \]  

(3.3-35)

When \( A_{nn} = 1 \) and equating for \( X_n \) the result yields
\[
X_n = Y_n - \left[ \sum_{n'=1}^{n-1} A_{nn'} X_{n'} + \sum_{n'=n+1}^{N} A_{nn'} X_{n'} \right] \quad (3.3-36)
\]

This is used for the iterative algorithm to obtain the source distribution \(X_n\) for all \(n\) between 1 and \(N\). The following equations are expressions of Equation (3.3-36) for the iterative step \(i\).

\[
X_1^{(i)} = Y_1 - \left[ 0 + \sum_{n'=n+1}^{N} A_{1n'} X_{n'}^{(i-1)} \right]
\]

\[
X_n^{(i)} = Y_n - \left[ \sum_{n'=1}^{n-1} A_{nn'} X_{n'}^{(i)} + \sum_{n'=n+1}^{N} A_{nn'} X_{n'}^{(i-1)} \right] \quad (3.3-37)
\]

\[
X_N^{(i)} = Y_n - \left[ \sum_{n'=1}^{N-1} A_{NN'} X_{n'}^{(i)} + 0 \right]
\]

For the first iterative step \((i = 1)\), the initial source distribution values can be assumed to be zero or equal to \(Y_n\). When performing iterations, each negative value of \(X_n\) is set to zero. Iterations are completed by like calculations, but reversed. The iteration \((i)\) moves from \(n = N\) to \(n = 1\), then the next iteration \((i + 1)\) would move from \(n = 1\) to \(n = N\), and so on. Equation (3.3-37) is the resolution to extracting the source distribution from the array characteristics of the beamformer’s output. The source distribution is the resulting output of the DAMAS beamforming algorithm.

In a study by Brooks and Humphrey, the DAMAS technique applied for aeroacoustic applications solved Equation (3.3-32) for \(X\) by means of Equation (3.3-31) for \(A_{nn'}\) and iterative process described in Equation (3.3-37); the first iteration started with \(X_n = Y_n\) [5]. DAMAS beamforming output presented a significant improvement in the resolution and accuracy of the results compared to traditional beamforming methods.
IV. Experiment Details

In order to design the necessary abatement to control the noise emissions from the 785B haul trucks adequately, a set of detailed experiments were established for which the use of NSI measurement techniques was paramount. This is in contrast to the typical approach to abatement design, which relies on a trial and error effort for noise reduction. The use of NSI allows for a more accurate identification of the various significant sources of noise, which make up the overall noise signature for the mining haul truck. It also allows for the ranking of the various noise sources to allow for focus on the most significant sources first. A thorough literature review failed to find other examples of using NSI for large mining vehicles.

The typical operating scenario for the haul trucks is both the moving drive-by of the truck as well as the stationary condition with wide-open throttle (WOT). As such, two experiments for the NSI tests were established. Further, both of these scenarios were tested for the cases for the haul trucks with and without the installation of an acoustic louvre installed in front of the trucks grill. The louvre which was specified and installed prior to the NSI tests, was chosen from a catalogue and is intended for permanent building applications such as for compressor rooms or buildings housing emergency generators. However, given the size and weight of the structure of the haul truck, the chosen louvre was well suited for this application. This chapter details the equipment and instrumentation used for the tests as well as the design of the procedures implemented for all the measurements.
4.1 Experimental Setup

The general setup in terms of the hardware and acquisition software setup was common for both the pass-by and the stationary NSI measurements. The specific unique details for each of the tests is given in the respective measurement sections that follow.

As outlined in Chapter 3, noise source identification using beamforming requires a microphone array to measure the noise before the determination of the location of the noise sources is possible. For the pass-by and stationary measurements, two different Brüel & Kjaer (B&K) microphone arrays were used. In both cases, an irregular microphone array was required to optimize the beamforming output as will be described in future sections.

The data acquisition front-end system that was used to interface with the microphone arrays was a Bruel & Kjaer (B&K) 60-channel LAN XI data acquisition front-end. The accompanying acquisition software was B&K Pulse Labshop software. Using this, recordings of the noise data were subsequently post-processed using the beamforming algorithms to generate the noise contour maps.

4.2 Pass-by (Operating) Measurements

4.2.1 Equipment and Instrumentation

As detailed previously, the haul trucks tested for this research are Caterpillar type 785B mining haul trucks operated at the GoldCorp Timmins mine. The entire haul truck fleet at this mine is of the same model and design, excluding one truck that had an acoustic louvre installed on the front grill sometime the previous year as a preliminary attempt to abate the truck’s noise emissions. For this study, both the truck with the louvre and another truck without were used for all the testing. Due to access limitations to the haul trucks, the
testing of additional vehicles to better ensure repeatability of the acquired data was not possible. The fleet of 785B vehicles was purchased within a year’s timeframe and all are of the exact same make and model. With this knowledge, the test results of the vehicles with and without the louvre installed was assumed to be representative of the entire fleet. The reason for this is that while the louvre did improve the level of noise from the truck, the amount of attenuation was not enough. As a result, this study was intended to evaluate the effectiveness of the louvre better and to recommend further abatement to better the generated noise emission levels.

To acquire the NSI data for the pass-by tests, the B&K 30-channel pentangular microphone array shown in Figure 16 was used. This large 3-metre diameter array was selected because it was specifically designed to facilitate NSI of large noise sources at far distances. As such, the pentangular array was well suited for this application.

Figure 16 – Bruel & Kjaer pentangular microphone array setup for pass-by measurements.
4.2.2 Experimental Design Setup and Procedure

The pass-by measurements were taken to get a picture of all of the noise emitting sources for the haul truck while it is moving and under load to represent the conditions along the haul road. For these tests, the position and speed of the truck were controlled in order to achieve consistent results between tests.

The haul truck operators were instructed to drive by, and in some cases, towards the acoustical array in order to acquire the representative data. In each case, the drivers were instructed to drive the vehicle in first gear and WOT, to simulate a worst case operating condition. In addition, all tested vehicles were carrying a full load. The intent for these conditions was create a controlled test environment to acquire meaningful and repeatable results.

To capture all the sound from a passing haul truck, the array was positioned such that its focal point was locked to the vehicle. To do so, the array was slowly rotated on the tripod as the vehicles passed. An illustration of the measurement setup showing the vehicle path is given in Figure 17.
During the tests, the vehicles were driven along a slight bend, which allowed for the distance from the array to the source to remain constant for the duration of the recording, as illustrated by the arc in Figure 17. To acquire data for both the driver and exhaust (passenger) sides of the vehicle, the haul truck was driven past the array from both the left and right directions along the same path. This allowed for measurements of both sides of the vehicle without the need to move the array. In addition to the pass-by measurements, data was taken with the same pentangular array with the haul trucks driven directly toward the array. This measurement allowed for the identification of any noise contributors located at the front of the vehicle during operation. More importantly, this allowed for the comparison of the trucks with and without the acoustical louvre installed in front of the vehicle’s grill.

Before the data could be acquired, it was necessary to configure the B&K Pulse acquisition software. The first step was to configure the 36 microphones to the geometry of the array. Figure 18 illustrates the geometry of the pentangular array as it was imported.
into the acquisition software. Next, the microphone signals were paired with their location on the imported geometry so that the software would be able to identify the spatial configuration of the microphones to allow for the NSI post-processing. The signal arrangement is illustrated in Figure 19.

Once the hardware settings were specified, the measurement settings were required to be set. For these, the frequency span was set to 6.4 kHz with a focal distance of 25 metres (the distance from the array to the vehicle) and the recording was specified to be post-processed using refined beamforming. Knowing the focal distance, the software knows the

![Array View](image)

Figure 18 – 30-channel Pentangular Array Geometry as Imported into Bruel & Kjaer Pulse Labshop.
Figure 19 – Microphone configuration table for pass-by NSI measurements from B&K Pulse Labshop.

position of the beamforming calculation plane. Once triggered, the software took five seconds of data followed by a photograph of the object, in this case, the haul truck. These settings were a compromise to facilitate a large frequency acquisition range for the NSI measurements given the quasi-steady nature of the moving source.
4.2.3 Environmental Considerations

The first set of field measurements for this study (before abatement was installed) were made on the property of GoldCorp’s Dome Mine site in South Porcupine, near Timmins, Ontario. The haul trucks were driven on a wide-open area far from other mining activities to ensure that the background noise level was sufficiently lower than the noise emissions from the haul truck. The temperature was approximately -10 degrees Celsius with a moderate wind not exceeding 15 km/h.

4.2.4 Measurement Procedure

As no measurement standards exist for the acquisition for NSI data, the following procedure was developed and is given as follows:

1. The operators of the 785B mining haul trucks were instructed to operate the vehicle in first gear at maximum RPM.

2. Trucks were loaded before entering the measurement area.

3. The 785B haul truck was driven pass the array setup along a specified path with the driver’s side of the vehicle facing the array.

4. The pentangular array was focused to the centre of the vehicle.

5. A five second measurement was acquired during the vehicle pass-by when the truck was at the nearest to the array.

6. Steps 2-5 were repeated with the exhaust side facing the array and again with the vehicle driving towards the array in a head-on scenario.

7. Steps 2-5 were repeated with the vehicle driving towards the array.
8. Steps 2-7 were performed using two different trucks; one with and another without the acoustic louvre installed on the front grill.

Typically, a measurement distance of 15 metres is used for single microphone pass-by measurements [17]. For the NSI pass-by measurements conducted during this research, a greater measurement distance of 25 metres was used for reasons of safety.

4.3 Stationary (WOT) Measurements

4.3.1 Equipment and Instrumentation

The measurements for the case for the stationary truck used, for the most part, the same equipment as the pass-by measurement. The only exception was the microphone array. The purpose of the stationary measurement was to get a more detailed and closer look at the various sources of noise. This requires a smaller array, and in this case, a greater number of microphones on the array. As was the case for the pass-by measurements, two haul trucks were evaluated; one with and the other without the acoustic louvre installed on the front of the vehicle.

The B&K 60-channel circular sector array, shown in Figure 20, was used. Compared to the pentangular array, this array was selected due to its application for closer range applications requiring higher spatial resolution. The software used for the acquisition and post-processing components of the measurements was the same as that used for the pass-by measurements.
Figure 20 – Stationary (WOT) measurement setup with 60-channel circular sector array and B&K LAN XI data acquisition system.

4.3.2 Experimental Design Setup and Procedure

The purpose for the stationary measurements was to acquire a more detailed high resolution noise map of the entire haul trucks. While these measurements were not fully representative of the noise emissions during a typical haul truck operation, the truck was operated at full throttle. However, the outcome from these measurements are able to give more detail to the noise source locations due to the permitted closer proximity to the vehicle compared to the pass-by tests. Further, with the increased number of microphones, the circular array is capable of increased spatial resolution compared to the pentangular array. As such, the generated noise map is able to show results that are ‘zoomed in’ to the sources
initially identified during the pass-by measurements results. In other words, the individual sources are more easily identified and differentiated.

In order to get a noise map for the entire haul truck, the vehicle was divided into several sections. A noise map was created for each one of these sections and then stitched together to result in one single complete contour map. The vehicle’s front and rear was divided into four separate section for which the results were combined into a single contour plot covering the entire vehicle front. It was found that no significant noise emissions were measured from the rear of the vehicle and as such the analysis of this part of the truck was emitted from the study. Similarly, the same was done for the sides of the vehicle with specific focus given to the strongest noise emitting components. It should be noted that for the 785B without the acoustic louvre, the side of the vehicle was instead divided into six sections with the intent to focus on areas not abated by the louvre in the hope to get more detailed noise emission data. However, this was subsequently found to be unnecessary as a division of four was found to be sufficient.

The array, which was located approximately 3 metres from the vehicle, was aligned to focus on the centre of each respective measured sector as illustrated in Figure 22. The geometry setup and microphone configuration for the circular array is shown in Figure 22 and Figure 23 respectively.
Figure 21 – Stationary NSI measurement array positions.

Figure 22 – 60-channel circular sector array as imported into B&K Pulse Labshop.
Figure 23 – Microphone configuration table for stationary NSI measurements from B&K Pulse Labshop.

An acquisition time of ten seconds was utilized for these measurements. This time period was found to be sufficient to acquire a good measurement for the NSI post-processing of this experimental setup. Using a frequency range of 6.4 kHz, the refined beamforming algorithm were used. This is the same frequency range and calculation method used for the pass-by measurements. Two measurements were taken for each sector of the mining vehicle. After the data was acquired, it was processed using the B&K Array...
Acoustic Post-Processing and the resulting noise maps were compiled into one overall haul truck noise map.

### 4.3.3 Environmental Considerations

As in the pass-by measurements, the stationary measurements were conducted outdoors near to the same location as the pass-by measurements. The haul truck was parked off the haul road and away from other operating equipment. This ensured that the background levels did not interfere with the quality of the measurements.

### 4.3.4 Measurement Procedure

For this measurement setup, following the same procedure was particularly crucial since the measurement results were then to be meshed together to produce an overall NSI sound intensity level map. The procedure utilized was as follows:

1. A loaded 785B haul truck was positioned in an open area.

2. The operator was instructed to WOT in neutral to produce high engine noise while remaining stationary.

3. The circular array was positioned three metres from the truck with the focal point directed at the centre of a specified section of the truck.

4. Two 5-10 second measurements were taken.

This procedure was followed for every section the vehicle was sub-divided into in order to acquire enough data to produce a full sound intensity level map. Measurements were taken with the array at each position as specified in
Figure 21, with the measurement taken having a focal point centred at the top section of the vehicle and another centred at the bottom section of the vehicle.

4.4 Sound Pressure Level Recordings

4.4.1 Equipment and Instrumentation

For the sound pressure level measurements of the vehicle, a Bruel & Kjaer Type 2270 dual channel sound level meter (SLM) was used. The Type 2270 meter is capable of acquiring many different sound metrics as well as a high quality signal recording that can later be post-processed for additional metrics if desired. This compact handheld instrument, illustrated in Figure 26, is both easy and convenient to use when recording in harsh environments. A tripod was used for measurements using the Type 2270 to ensure that the operator did not interfere with the measured sound field.

Figure 24 – B&K Sound level meter type 2270 measuring haul truck noise.
4.4.2 Experimental Design Setup and Procedure

The sound pressure level measurements were taken with every NSI measurement during the pass-by and stationary measurements before and after abatement and again with and without the exhaust silencer installed. Note that the exhaust silencer measurements were only performed while the vehicle was stationary. The sound pressure level data is versatile in that it can show immediate overall effects of applied abatement treatment.

The Type 2270 meter was used to acquire short term $L_{eq}$ noise data, take 10 second recordings for later post-processing and calculation of sound power levels, and also acquire 1/3-octave spectra. The spectra data was later used to model the expected attenuation for the various proposed abatement materials. The instrument was located next to the array, and at the same distance between the source and the meter’s microphone; but at a slightly lower height than the array. The recording durations were equivalent to the NSI measurement lengths.

Additional sound pressure level measurements were acquired for the truck to evaluate the effectiveness of the installed custom built hospital grade muffle. A hospital grade muffler is designed to give greater reduction to noise emissions, in order to comply with environments requiring a higher standard of attenuation (i.e. hospitals). These measurements were taken for the case with the muffler installed and removed. These measurements (two each) were taken at a distance of five metres from the exhaust port of the haul truck vehicle. The exhaust port height was approximately three metres and the microphone height for the Type 2270 was 1.4 metres. The measurement setup is shown in Figure 25.
Lastly, after one of the haul trucks was equipped with the prototype abatement, the Type 2270 meter was used again to acquire the pass-by data for the abated trucks, with and without the proposed abatement solution.

### 4.4.3 Environmental Considerations

Sound pressure level measurements were conducted at several locations at the GoldCorp facility, depending on whether the data was for the pass-by tests or stationary tests. Some of these were performed in the open pit area while others were taken near the maintenance building for convenience. This was done for ease of access to tools for the removal of the exhaust silencer. Taking noise measurements near large buildings can pose issues with acoustical measurement results due to reflection off any nearby structures. Although the haul truck was positioned away from the maintenance bay, caution was taken when acquiring the noise measurements. In addition, all data was collected during periods of minimal ambient noise.
4.4.4 Measurement Procedure

The measurement procedure used for the acquisition of the sound pressure level data was simple due to the ease of use of the B&K Type 2270 handheld meter. The SLM was set up to take sound signal recordings displays in real time the overall and 1/3-octave L_{eq} values. The acquired recordings would later be post-processed for further analysis. The following outlines the general procedure followed for sound pressure level signal recordings:

1. Pass-by Measurements
   
   a. The Type 2270 SLM was mounted on a tripod and positioned approximately 25 metres from the 785B vehicle’s path.

   b. The 785B vehicle operators were instructed to pass by the SLM in first gear WOT.

   c. A 5-10 second recording was taken while the 785B vehicle passed by the SLM and the pentangular array (the acquisition time varied depending on the time the vehicle took to pass the SLM).

   d. The pass-by recordings were repeated for the cases with and without the added prototype abatement.

2. Stationary Measurements

   a. The SLM was positioned beside the circular array three metres from the truck for the stationary NSI measurements.
b. The 785B operator was instructed to operate with WOT in neutral gear to produce a high level noise emission.

c. A 5-10 second recording were taken simultaneous with the array measurements.

d. The SLM was moved around the vehicle to various locations alongside the array.

e. Recordings were repeated for the vehicle with the abatement material applied.

3. Exhaust Comparison

a. The SLM was positioned five metres from the exhaust to the 785B haul vehicle.

b. With the silencer installed, the vehicle operator was instructed to operate with WOT in neutral gear.

c. A ten second signal recording was taken while the truck was operating.

d. The data acquisition was repeated with the silencer removed.
V. Data Analysis and Discussion

5.1 Preliminary Analysis Outline

Using the acquisition methods described in the previous chapter, the collected noise data was post-processed and analyzed using different techniques and software. This chapter details the analysis process along with discussion of the results.

Once the data was acquired using B&K Pulse Labshop, it was imported into the Array Acoustic Post-Processing application for the processing of the NSI results. For this, the refined beamforming algorithm was used to process the results. The refined beamforming approach uses the non-negative least square (NNLS) algorithm, which is a derivation of the deconvolution beamforming method and was chosen as it can give the highest spatial resolution. For both the pass-by and the stationary measurements, sound intensity levels were calculated over the frequency range of 50 Hz to 5 kHz in 1/3-octave frequency bands. The benefit of getting a sound intensity level map is that the sound power level can be easily calculated by performing a simple integration over a chosen region on the sound intensity map. This eases the quantification of the impact of sub-sources and regions on the overall noise emissions for the mining haul truck. Using overall and 1/3-octave sound power levels, the contribution of each sub-source to the overall noise contribution and the frequency band contributions were ranked. These comparisons can give valuable insight on where to target applications of noise control.

The purpose of the NSI results was to rank and identify the locations of significant noise contributors to the overall noise emission of a 785B haul truck. This information can be used to identify and design effective abatement for the haul trucks and to predict the
anticipated abated noise levels. This essentially eliminates much of the trial and error effort that is often used for these cases.

In addition to the identification and ranking of the significant noise contributors on the truck, a comparison between the truck with and without the acoustical louvre was performed. With isolation of the sources in both scenarios, the quantified sound power levels of the isolated areas were compared. This comparison quantified the effect of the louvre for both the pass-by and the stationary measurements so that a decision could be made as whether or not to equip the entire haul truck fleet.

5.1.1 Pass-by Measurement Comparison and Analysis

The pass-by measurements acquired consisted of raw array data that required post-processing with a noise source identification algorithm to yield NSI results. For this study, refined beamforming was used to process the array data. As discussed previously, refined beamforming is an expansion of the standard delay and sum beamforming by means of an iterative deconvolution methodology. B&K Array Acoustic Post-processing software is well equipped with various NSI algorithms; such as the NNLS refined beamforming algorithm. This method was selected due to the increased spatial resolution compared to its counterpart, the delay and sum. The high spatial resolution is desired due to the accuracy required to identify finer noise contributors within a large source. Refined beamforming is capable of differentiating sub-sources precisely which allows for fewer assumptions in the determination of noise contributors, compared to DAS beamforming.

With the specified algorithm, the quasi-stationary processing type was used for the pass-by measurements. A quasi-stationary processing type allowed the beamformed results
to be displayed over a period of time. By averaging with an interval width of 0.5 seconds over a five-second recording, 10 NSI contour maps and sound power level plots were generated with the goal to display the change in the emissions from the source with respect to time. Using this approach, a representative time interval was selected to represent the full duration of the measurement for simplification of the results.

For simple interpretation of the results, intensity was selected as the beamformer’s output. Given that sound intensity has a magnitude as well as direction, it is optimal for the representation of the flow of acoustical energy within an acoustic field. The benefit to using sound intensity is that the integral over a specified area on the noise map gives sound power. The sound power level is an ideal metric for the comparison and ranking of the noise contributors in relation to the overall noise emission of the haul truck.

With the employment of refined beamforming, using the specified settings, the resulted outputs were analyzed for the identification and ranking of the noise sub-sources for the truck. An example of the beamformer’s output for the driver side of the vehicle with the acoustical louvre is shown in Figure 26. The A-weighted results for the exhaust, driver, and front measurements of the truck with and without the acoustical louvre are given in Appendix A (A 1 through A 6). The contour plots illustrate the sound intensity level on the specified colour scale provided with the noise maps. For these results, individual scales were used for each measurement relative to the sound level measured. This allowed for the best colour scale for each measurement to be used for accurate identification of noise contributors. In addition, this reduced the error in the interpretation of the NSI results. It is very important to note that the scales varied for all noise maps in this section when looking at the analysed results.
Figure 26 – A-weighted sound intensity level noise map from the driver’s side of the 785B mining haul truck with aftermarket acoustical louvre.

Once processed, the results were interpreted to identify the regions of significant noise emissions. Figure 26 shows that significant noise was emitted from the wheel wells and undercarriage of the mining vehicle. For this colour scale, bright yellow represented the most acoustical energy while light green represented a lesser acoustical energy. Thus, the origins of noise emissions were depicted by the bright yellow regions on the sound intensity maps. Using this criteria, sub-sources were identified for all pass-by measurement results in Appendix A.

Pass-by NSI measurements were conducted to depict the regions of significant noise contribution to the overall noise emission representative of the 785B vehicle’s regular operation. In Appendix A, figures A 1 through A 6 present the results in which the significant sub-sources are identified. For both vehicles, the regions of the highest acoustical energy are similar. Figure A 1 shows the driver side pass-by sound intensity map for the 785B with the acoustical louvre, which is compared to A 4, the driver side pass-by sound intensity map for the 785B without the acoustical louvre. For both of these scenarios,
the wheel wells and undercarriage emitted the most acoustical energy. Thus, it is justified that the wheel well on the driver side of the vehicle is a significant sub-source for the overall noise emission. All the results were compared for both vehicles to justify the consistency of results and validate the identified sub-sources. Figure A 2 is compared with A 5 for the exhaust side pass-by results and A 3 is compared with A 6 for the head on pass-by results. All of the NSI results conclude that the wheel well on both sides of the vehicle, the exhaust, and the front grill are the most significant noise contributors to the overall noise emission of the 785B mining vehicle. Although an inspection of the vehicle could predict many problem noise contributors, not all problem areas identified would have an impact on the overall noise emission of the vehicle. The NSI results, however, more accurately identified the problem areas which most significantly contributed to the overall noise emissions of the vehicle.

The intention of the pass-by results is to identify and rank the significant noise contributors. Therefore, to understand the impact of these noise contributors, isolation of the sub-sources must be conducted to quantify the impact on the overall noise emissions. Source isolation for the pass-by measurements was done in the Array Acoustic Post-processing software by selecting a region on the noise map to calculate the sound power level. The calculated and displayed sound power level is representative of the isolated sub-source. Using this method, the identified regions in the preliminary pass-by analysis (the front grill, wheel wells, exhaust, and undercarriage regions) are isolated for quantification of their impact on both of the vehicles’ noise emissions. Figure 27 displays source isolation results for the pass-by measurements. All isolation results are presented in Appendix A (A 7 through A 12).
The wheel well area shown in Figure 27 is isolated and the 1/3 octave sound power level constant percentage band (CPB) plot is generated for the measurement. This region was isolated since it was previously identified as a significant noise contributor to the overall noise emission. The A-weighted sound power level for this region is determined to be 109 dBA. Compared to the overall A-weighted sound power level for the entire vehicle measurement of 117 dBA, the wheel well noise contribution is determined to be significant. In addition, from inspection of the 1/3 band sound power level plots, it is apparent that the overall noise emission is primarily due to the emission of the isolated region. Sound power levels were extracted from A 1 through A 6 for all identified sub-sources as given in Figure 27.

Figure 27 - A-weighted sound intensity level noise map for the driver’s side of the 785B mining haul truck with acoustical louvre.
The sound power level values extracted from the measurements were used to quantify the impact on the overall noise emission of the vehicle. The sound power levels were computed for the entire measurement area and the isolated region as detailed above. The sound power level for the pass-by results are presented in Tables 2 and 3.

Table 2 – Overall sound power levels for the 785B mining vehicle pass-by measurements with and without the acoustical louvre.

<table>
<thead>
<tr>
<th>Noise Contributor</th>
<th>No Louvre dB(A)/1p W</th>
<th>Louvre dB(A)/1p W</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust/Wheel Well - Exhaust Side</td>
<td>122</td>
<td>119</td>
<td>3</td>
</tr>
<tr>
<td>Wheel Well - Driver Side</td>
<td>122</td>
<td>117</td>
<td>5</td>
</tr>
<tr>
<td>Front Grill</td>
<td>120</td>
<td>111</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 3 – Isolated source sound power levels for the 785B mining vehicle pass-by measurements with and without the acoustical louvre.

<table>
<thead>
<tr>
<th>Noise Contributor</th>
<th>No Louvre dB(A)/1p W</th>
<th>Louvre dB(A)/1p W</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust/Wheel Well - Exhaust Side</td>
<td>116</td>
<td>108</td>
<td>8</td>
</tr>
<tr>
<td>Wheel Well - Driver Side</td>
<td>115</td>
<td>109</td>
<td>6</td>
</tr>
<tr>
<td>Front Grill</td>
<td>114</td>
<td>101</td>
<td>13</td>
</tr>
</tbody>
</table>

The sound power levels determined through the integration of the sound intensity maps. The sound power levels were used to quantify the impact of each noise contributor for comparative and ranking purposes. A comparison was conducted for both the isolated sub-sources and the overall measurement of the sound power levels to understand the impact contributed by the sub-sources alone and the overall levels emitted by the vehicle. Thus, the comparison for both scenarios quantified the magnitude of noise emission by each sub-source such that the sub-sources could be compared and ranked relatively.
Table 2 and Table 3 show the overall and isolated sound power levels for the vehicles with and without the acoustical lover. By comparing these results, quantification of the performance of the acoustical louvre is possible to determine if the louvre provides adequate abatement at the vehicle’s front grill. Table 4 shows the resulting reduction realized by the addition of the acoustical louvre. It was found that the reduction within the isolated sub-sources is larger than that of the entire measurement region. In the overall measurement level, the acoustical energy from the sub-source and background acoustical energy is included in the computation of sound power level. In contrast, the isolated sub-source sound power levels only account for the acoustical energy emitted directly from the sub-source. Naturally, the contribution of noise from the isolated area has a lower sound power level than that of the overall measurement. Thus, the reduction is expected to be greater when comparing isolated values since the contamination from other sources is not a factor. The reduction in sound power level for the sub-sources represents the impact of the acoustical louvre directly at the sub-source; while the reduction in the overall measurement represents the decrease in the trucks overall noise emission from the vehicle face. The overall measurement accurately depicts the truck’s overall emissions; therefore, the overall measurement is used to quantify the effect of the acoustical louvre. As shown in Table 4, a reduction of 9 dB is achieved at the front of the truck. This is a significant result since a 10 dB reduction is perceived to be half as loud. Small reductions of up to 5 dB are also noted at the sides of the vehicles. For the pass-by reductions, for both the isolated and overall sound power level, the acoustical louvre is recommended as a viable abatement solution to reduce the noise emissions for the front grill of the truck.
Table 4 – Reductions in overall and isolated source sound power level for the 785B mining vehicle pass-by measurements.

<table>
<thead>
<tr>
<th>Noise Contributor</th>
<th>Overall Reduction (dB)</th>
<th>Isolated Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust/Wheel Well Exhaust Side</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Wheel Well Driver Side</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Front Grill</td>
<td>9</td>
<td>13</td>
</tr>
</tbody>
</table>

For both the overall and isolated source results, the acoustical louvre was successful in reducing the noise emissions from the front grill. In addition, a small reduction in sound power level from both sides of the vehicle was found. This finding is explained by the louvre being constructed of absorptive material; thus, some noise energy emitted from the engine and interior mechanisms will be absorbed.

Other identified sub-sources required further analysis in order to recommend abatement treatment that will adequately reduce the overall noise emission of the vehicle. However, before recommendations can be given, additional measurements were conducted and analyzed to reinforce the findings of the pass-by results with greater accuracy. Also, as specified earlier in this chapter, the ranking of the noise contributors is required to understand their relative impact on the overall noise emissions. The ranking analysis is computed and provided later in the chapter.

5.1.2 Stationary Measurement Comparison and Analysis

The purpose of the stationary measurements was to better facilitate the generation of a high-resolution noise map of the entire haul truck. Due to safety requirements in regard to proximity to the moving haul trucks, high resolution data could not be acquired. If these
restrictions were not in place, a smaller array with the ability to take higher resolution NSI data would have been used for the pass-by measurements at a closer measurement distance. This would have eliminated the need for the stationary tests. Since, the smallest measurement distance was 25 metres during the pass-by measurements; the stationary test was used to take measurements from a closer measurement distance, and in turn, allowed for the use of an array that can provide higher resolution NSI results.

From the pass-by measurements, the sides of the vehicle were identified as significant noise contributors; but separation of smaller noise sources was left up to the analyst’s judgement. By employing measurements with a higher level of spatial refinement, separation and quantification of smaller sub-sources on the vehicle sides and front was obtained. The overall noise map was created by post-processing several measurements from various views of the vehicle using the stationary NNLS refined beamformer and then stitching them together.

As describe for the pass-by analysis, sound intensity was calculated for the development and presentation of the noise map. The sound intensity level maps identify the significant noise contributors and are able to calculate the sound power level for sub-sources through a simple integration.

Although the sound power level values are not representative of the noise for the condition of a driving vehicle, valuable insight on the ranking and location of the sub-sources can be found and provided due to the high spatial resolution. In order to acquire numerous measurements in a control environment to produce the result for an entire
vehicle, it is required that the truck be fixed in a given position. This allows the array to be reoriented to acquire data that can be easily combined.

The noise map for the truck with the acoustical louvre is given in Figure 28. Here, specific areas such as the front grill and wheel wells are refined to display the contours with a greater spatial resolution, as well as the location of the noise contributors. From the pass-by analysis, only the front grill was detected and it was discovered that the front grill on the driver side of the vehicle had a larger contribution than that of the exhaust side. Information regarding sub-source specific location allowed further research to determine the components responsible for this noise emission.

Figure 29 illustrates the sound intensity map of the mining vehicle without the acoustical louvre. Shown are the two sides and rear view of the truck. It was not necessary to acquire the data for these views using the truck outfitted with the acoustical louvre.

The results of the stationary NSI test reinforced the conclusions from the pass-by NSI measurements. Through the same interpretation method used for the pass-by results, the noise contributors were determined from the sound intensity level maps. For these results, a unified sound intensity level contour colour scale was used. Thus, the significant sub-sources may not be highlighted in bright yellow as in the pass-by scenario. A unified scale was used to provide comparable results between the truck with and the truck without the acoustical louvre. Careful consideration of colour contours must be considered. Here, the dark green represents the largest impact for the haul truck with the louvre and for the case of no acoustical louvre, dark green as well as bright yellow depicted the significant
Figure 28 – A-weighted sound intensity level map of entire 785B mining vehicle with acoustical louvre.
Figure 29 – A-weighted sound intensity level map of entire 785B mining vehicle without acoustical louvre.
sub-sources. With this interpretation, the front grill, wheel wells, undercarriage, and exhaust are the main noise contributors to the 785B noise emission. The pass-by NSI results may have been sufficient in the identification of these regions but the stationary results conveyed more accurate locations for the noise contributors.

As shown in the above figures, the front grill noise emission was more accurately determined to be emitting from the driver side of the front grill. With this finding, an investigation of the truck components and possible noise sources was carried out to determine the source of the noise. With the additional spatial information obtained in these series of measurements, potential error in the interpretation of the results is lessened for the identification of the components responsible for the noise emission.

As performed for the pass-by results, the isolated areas of significant noise emission are analyzed using the Array Acoustics Post-processing software. The region of interest is outlined within the software, and from there the overall and the 1/3-octave band sound power levels are calculated. Next, comparison of the sub-source emissions was conducted. The purpose of the comparison is to quantify the impact of the noise contributors and rank them relative to one another, as was performed for the pass-by measurements. These results were determined to reinforce the finding from the pass-by measurements, only here with greater accuracy in the localization of the sources. Identification of the noise contributors in the stationary measurement sound intensity maps are given in Appendix B with an example shown in Figure 30.

Using this approach, with the stationary sound intensity maps, the sub-sources are more accurately identifiable and any sub-sources that are near to one another are more
easily separated. In turn, a better calculation of the individual sub-source contributions was facilitated. In Figure 30, the origin of the noise emission in the measurement is better isolated to illustrate the impact of the sub-source. This isolation process was performed for all measurement sections of the front grill and the two sides of the vehicles. These results are presented in B 1 through B 17.

Figure 30 - Isolated A-weighted stationary sound intensity level noise map of the lower front passenger side of the 785B mining haul truck with acoustical louvre.

The determined sound power levels of the overall measurement and the isolated sources for the resultant sound intensity maps shown in Appendix B are presented in Tables 5 through 8.
Table 5 – Overall sound power levels for each section of the front grill of the 785B vehicle stationary measurements with and without the acoustical louvre (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>No Louvre (dB(A)/1p W)</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Passenger Lower</td>
<td>117</td>
<td>110</td>
<td>7</td>
</tr>
<tr>
<td>Front Passenger Upper</td>
<td>113</td>
<td>108</td>
<td>5</td>
</tr>
<tr>
<td>Front Driver Upper</td>
<td>115</td>
<td>109</td>
<td>6</td>
</tr>
<tr>
<td>Front Driver Lower</td>
<td>118</td>
<td>111</td>
<td>7</td>
</tr>
<tr>
<td><strong>Linear Average</strong></td>
<td><strong>115.75</strong></td>
<td><strong>109.5</strong></td>
<td><strong>6.25</strong></td>
</tr>
</tbody>
</table>

Table 6 – Overall sound power levels for each section of the 785B vehicle sides stationary measurements with and without the acoustical louvre (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>No Louvre (dB(A)/1p W)</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver Front Upper</td>
<td>106</td>
<td>105</td>
<td>1</td>
</tr>
<tr>
<td>Passenger Front Upper</td>
<td>116</td>
<td>112</td>
<td>4</td>
</tr>
<tr>
<td>Passenger Front Lower</td>
<td>115</td>
<td>111</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 7 – Isolated source sound power levels for each section of the front grill of the 785B vehicle stationary measurements with and without the acoustical louvre (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>No Louvre (dB(A)/1p W)</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Passenger Lower</td>
<td>114</td>
<td>104</td>
<td>10</td>
</tr>
<tr>
<td>Front Passenger Upper</td>
<td>110</td>
<td>102</td>
<td>8</td>
</tr>
<tr>
<td>Front Driver Upper</td>
<td>112</td>
<td>101</td>
<td>11</td>
</tr>
<tr>
<td>Front Driver Lower</td>
<td>116</td>
<td>107</td>
<td>9</td>
</tr>
<tr>
<td><strong>Linear Average</strong></td>
<td><strong>113</strong></td>
<td><strong>103.5</strong></td>
<td><strong>9.5</strong></td>
</tr>
</tbody>
</table>
Table 8 – Isolated source sound power levels for each section of the 785B vehicle sides stationary measurements with and without the acoustical louvre (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Isolated Region</th>
<th>No Louvre (dB(A)/1p W)</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver Front Upper</td>
<td>Wheel Well</td>
<td>102</td>
<td>99</td>
<td>3</td>
</tr>
<tr>
<td>Passenger Front Upper</td>
<td>Exhaust</td>
<td>105</td>
<td>103</td>
<td>2</td>
</tr>
<tr>
<td>Passenger Front Upper</td>
<td>Wheel Well</td>
<td>109</td>
<td>104</td>
<td>5</td>
</tr>
<tr>
<td>Passenger Front Lower</td>
<td>Wheel Well</td>
<td>109</td>
<td>106</td>
<td>3</td>
</tr>
</tbody>
</table>

These tables give the sound power levels for the overall measurements as well as the isolated sources for both of the tested 785B vehicles (with and without the acoustical louvre). As shown in the pass-by results section of this chapter, the reduction in the sound power level was computed for the addition of the acoustical louvre. This attenuation is expected since the vehicle was stationary during measurements and thus resulting in the engine being less loaded and producing a reduced sound emission. Additionally, many mechanical components including the axles, drive train and tires were not operational, further reducing the overall noise emission of the vehicle. As such, the reductions for the stationary vehicle are less than the reductions found in the pass-by results. This was also observed for the noise emitted from the exhaust, wheel wells and undercarriage. As was described in the pass-by results section of this chapter, the sound power levels of the isolated sub-sources were determined such that the impact on the overall noise emission was quantified. With these overall and isolated source sound power levels, a comparison of the values was computed to determine the effectiveness of the acoustical louvre.

The reductions in sound power level with the addition of the acoustical louvre are presented in Table 5 through Table 8. The sound power levels are compared for the overall
results and isolated sub-source values to determine the overall reduction from each case and the reduction of the sub-source. The overall reduction was determined to be more appropriate by representing the perceivable loudness as this correlates better to a listener at a representative receptor location, and not just the sound emission of a single sub-source. In contrast, it is still worthwhile to compare the isolated sound power levels to quantify the reductions to the sub-sources. On average, the reduction of the overall measurement of the front grill was 6 dB in terms of sound power level. For the isolated source sound power levels, the reduction is determined to be 10 dB. As stated for the pass-by results, the isolated sub-source sound power level reductions should be greater since there was no influence on the measurement from the other sub-sources of the vehicle. A 6 dB reduction is a noticeable reduction in sound power level. Implementation of the acoustical louvre performance in the pass-by results is justified with the high spatial resolution stationary NSI results.

When comparing the sub-sources located on the sides of the vehicle, the reductions are less. The acoustical louvre is an absorptive device that absorbs some of the acoustical energy emitted by the engine. Since the engine shell noise is one of the most significant sources of noise emitting from the front grill, wheel wells and undercarriage, some of the acoustical energy is absorbed by the louvre and resulted in a reduction in sound power level. No abatement was applied to the wheel wells or undercarriage of the vehicle; thus, no reduction in sound power level was expected.

The noise contribution of the identified sub-sources is quantified through the sound power levels presented above. This quantification is later used for the ranking of noise contributors to determine their relative impact on the overall noise emission of the truck.
Later, the sound power levels computed for the stationary NSI results are used as the benchmark noise emission for the quantification of suggested noise abatement.

5.1.3 Noise Source Identification Results and Source Ranking

Noise sub-sources were identified through the analysis of the NSI measurements. The result presented previously in this chapter identified the significant noise contributors, or noise sub-sources, which now require the design of noise abatement. Both the pass-by and the stationary noise results determined the significant contributors to be the front grill, exhaust, wheel wells and undercarriage. Although the specified area may not have emitted the sound itself, internal mechanisms created the noise that ‘leaked’ from these regions of the haul truck. For these noise contributors, the engine shell noise was determined to be the primary contributor emitted from the non-enclosed 785B vehicle body. That is, the engine is exposed through the wheel wells and undercarriage. The engines used in these large mining vehicles are extremely loud and without any control, noise is emitted through every opening. The 785B grill requires significant airflow for engine cooling; thus, the addition of the acoustical louvre is not possible. With the understanding of the origins of the noise sub-sources, the proper interpretation of the results and source ranking is possible to design an effective noise abatement plan for the 785B haul truck.

The ranking of noise contributors was determined separately for the pass-by and the stationary results; then with the author’s judgement, the overall rank was determined. To begin, the ranking of the pass-by sub-sources was determined. Table 9 presents the ranking of the noise contributors for the pass-by measurements isolated to the highest spatial resolution possible for such a measurement. For the pass-by measurements, limitations were present in isolating the emissions originating from the exhaust, wheel
wells and undercarriage due to the spatial resolution of the result. The stationary measurements presented later in this section are better for the isolation of these sub-sources. Ranking was assigned on a scale from one to three with one representative of the most significant noise contributor and three having the least significant contribution.

It is observed that the front grill has the least contribution for both the truck with and without the acoustical louvre. In addition, the exhaust/wheel well/undercarriage on the passenger side and the wheel well/undercarriage on the driver side were within one decibel of each other for both cases. This difference is insignificant although their ranks are technically different when quantified, the sub-sources should be perceived as possessing the same noise contribution.

Table 9 – Ranking of isolated noise contributors identified through pass-by measurement NSI results (A-weighted).

<table>
<thead>
<tr>
<th>Isolated Sub-Sources</th>
<th>Louvre</th>
<th>No Louvre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L_w (dB(A)/1p W)</td>
<td>Rank</td>
</tr>
<tr>
<td>Exhaust/Wheel Well/Undercarriage</td>
<td>108</td>
<td>2</td>
</tr>
<tr>
<td>Wheel Well/Undercarriage</td>
<td>109</td>
<td>1</td>
</tr>
<tr>
<td>Front Grill</td>
<td>101</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 10 – Ranking of isolate noise contributors identified on the front grill of the 785B haul trucks through the stationary measurement NSI results (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>No Louvre (dB(A)/1p W)</th>
<th>Rank</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Passenger Lower</td>
<td>114</td>
<td>2</td>
<td>104</td>
<td>2</td>
</tr>
<tr>
<td>Front Passenger Upper</td>
<td>110</td>
<td>4</td>
<td>102</td>
<td>3</td>
</tr>
<tr>
<td>Front Driver Upper</td>
<td>112</td>
<td>3</td>
<td>101</td>
<td>4</td>
</tr>
<tr>
<td>Front Driver Lower</td>
<td>116</td>
<td>1</td>
<td>107</td>
<td>1</td>
</tr>
<tr>
<td>Linear Average</td>
<td>113</td>
<td></td>
<td>104</td>
<td></td>
</tr>
</tbody>
</table>
Table 11 – Ranking of isolate noise contributors identified on the 785B haul trucks through the stationary measurement NSI results (A-weighted).

<table>
<thead>
<tr>
<th>Vehicle Side</th>
<th>Noise Contributors</th>
<th>No Louvre (dB(A)/1p W)</th>
<th>Rank</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>Wheel Well</td>
<td>102</td>
<td>4</td>
<td>99</td>
<td>4</td>
</tr>
<tr>
<td>Passenger</td>
<td>Exhaust</td>
<td>105</td>
<td>3</td>
<td>103</td>
<td>3</td>
</tr>
<tr>
<td>Passenger</td>
<td>Wheel Well</td>
<td>109</td>
<td>2</td>
<td>106</td>
<td>1</td>
</tr>
<tr>
<td>Front</td>
<td>Front Grill</td>
<td>113</td>
<td>1</td>
<td>104</td>
<td>2</td>
</tr>
</tbody>
</table>

For the stationary results, the front grill sections were ranked individually; then the average of the front grill measurements were ranked against the other sub-sources. The resultant ranking of the noise contributors is given in Table 10 and Table 11.

The ranking of the front grill is conducted to understand the magnitude of the identified sub-sources in the sound intensity maps. Comparing each isolated noise contributor to one another gives the relative significance and outlines the effectiveness of the acoustical louvre. It should be noted that these results do not match up with the pass-by measurements due to the stationary measurements lacking the moving component and engine load associated noise present in the pass-by measurements. Therefore, it is apparent that the levels in the stationary measurement are lower with less engine shell noise escaping from the wheel wells and undercarriage. In turn, the ranking of the noise contributors for the stationary measurements would vary from the pass-by measurement. This was the case as presented in Table 11.

The highest ranked section of the front grill is the front driver lower measurement, which shows a significant source behind the front grill of the driver’s side of the vehicle.
Since this is identified to be the most significant source, it is safe to assume that the major cause of noise emissions from the front grill emanated from this region. With additional research, it is found that the engine turbo chargers are located on the driver side of the engine. Additionally, it is observed that the lower sections of the front grill emitted the most noise. This was due to the breakdown of sections. The upper sections were not emitting any major noise; thus, the sound power levels of the upper sections would be of lesser value than the lower sections. The lower sections of the front grill encompassed the majority of the engine. In conclusion, the higher rank of the lower sections in comparison to the upper sections is justified.

Table 11, the front grill was the most significant contributor for the truck without the acoustical louvre, followed by the wheel well on the passenger side, the exhaust, and the wheel well on the driver side. For the case with the acoustical louvre, the front grill was determined to be second in noise contribution. This observation displays the effectiveness of the acoustical louvre by showing that with the addition of the louvre the front grill is no longer the most significant sub-source. With this conclusion, focus on the design of the noise treatment is given to the other sub-sources.

With ranking of the sub-sources established for both the stationary and the pass-by results, an overall noise contribution ranking is possible. With consideration that the pass-by results represent a worst-case regular operation of the 785B mining vehicle, precedence is suggested for the pass-by results. Therefore, it was interpreted that the wheel wells and undercarriage are the most significant noise contributors and should be the primary focus for noise abatement. From analyzing the vehicle subjectively, the engine noise does radiate from the open wheel wells and undercarriage and is cause for concern. The next ranked
source is the exhaust. Given that the exhaust already has a custom hospital grade silencer, there is not much more that can be done to address this source. The performance of the silencer is quantified further in this chapter. Lastly, the front grill was found to be the least significant noise contributor. This conclusion is based on the fact that the front grill showed lower sound power level for the pass-by results relative to the other sub-sources and the fact that the front grill already had noise abatement resulting from an earlier study. As such, the front grill is not a priority for the design of additional noise abatement. With this in mind, the focus for the noise abatement is toward the wheel wells and undercarriage of the vehicle.

### 5.1.4 Exhaust Silencer Performance Comparison

In previous attempts to reduce the noise emissions for the 785B mining vehicles, GoldCorp installed hospital grade silencers from Silex Inc. on their entire fleet. These silencers were intended to reduce the vehicle’s exhaust noise emission. The manufacturer specifications claimed that the silencers would result in a significant reduction of the emissions of exhaust noise but the actual noise reduction was never quantified. Thus, a simple test was conducted to quantify the impact of the aftermarket exhaust silencer.

A SPL measurement of the truck with and without the silencer installed was conducted, as detailed in the experimental details section. Recordings were post-processed using B&K Reflex. The measurements were processed using an A-weighted 1/3-octave CPB analyzer. Figure 31 is an illustration of the Reflex processing chain for an A-weighted 1/3-octave CPB. As shown, an A-weighting was applied to the raw data followed by a 1/3-octave CPB analyzer.
Figure 31 – B&K Reflex A-weighted 1/3-octave CPB processing chain.

Following the post-processing, the SPLs were exported to Microsoft Excel for further analysis. Two recordings were processed for both the truck with the silencer installed and the truck without the silencer. Each 1/3-octave band was logarithmically averaged to produce a single value SPL for the truck with and without the silencer. The average SPLs were compared to quantify the silencer’s impact on the noise emission. The 1/3-octave results are presented in Table 12.

The comparison in Table 12 shows the performance of the aftermarket silencer and the quantified reductions in noise emission. From the data given in Table 12 the silencer is shown to perform better at the higher frequencies. The greater SPL levels are within the low to mid 125-4000 Hz range, where the silencer’s performance is poorest. Significant reduction is found at frequencies greater than 4000 Hz. This results in an insignificant overall A-weighted noise reduction of 1 dB. Although an abatement treatment was put into place the addition of this specific silencer did not result in appreciable abatement.
Table 12 – A-weighted 1/3-octave CPB comparison of the exhaust silencer.

<table>
<thead>
<tr>
<th>Frequency Band (Hz)</th>
<th>SPL Comparison 5.03 m</th>
<th>With $L_p$ (dBA)</th>
<th>Without $L_p$ (dBA)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>30</td>
<td>31</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>38</td>
<td>33</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>31.5</td>
<td>59</td>
<td>46</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>47</td>
<td>48</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>59</td>
<td>53</td>
<td>-6</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>68</td>
<td>57</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>59</td>
<td>60</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>75</td>
<td>72</td>
<td>-3</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>78</td>
<td>74</td>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>79</td>
<td>73</td>
<td>-6</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>86</td>
<td>78</td>
<td>-8</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>79</td>
<td>81</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>76</td>
<td>84</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>82</td>
<td>84</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>88</td>
<td>88</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>630</td>
<td>84</td>
<td>85</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>84</td>
<td>87</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>84</td>
<td>86</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1250</td>
<td>85</td>
<td>86</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td>85</td>
<td>86</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>82</td>
<td>86</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>81</td>
<td>83</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3150</td>
<td>78</td>
<td>81</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>74</td>
<td>79</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>72</td>
<td>79</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>6300</td>
<td>69</td>
<td>76</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>8000</td>
<td>64</td>
<td>71</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>59</td>
<td>68</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>12500</td>
<td>54</td>
<td>64</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>16000</td>
<td>47</td>
<td>59</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>20000</td>
<td>41</td>
<td>54</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Overall A (dB(A)/20μ Pa)</td>
<td>95</td>
<td>96</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
5.1 Suggested Noise Abatement

Through analysis, significant regions responsible for the noise emission of the 785B haul truck were identified. With the quantification of each noise contributor, an effective and efficient noise abatement treatment needs to be designed. This was done with previous attempts for abatement, to be kept in mind.

Analysis for abatement design was focused on the identified exterior noise sources. With this, an investigation to understand the mechanics associated with the vehicle’s engine was pursued. A disassembled 785B vehicle under maintenance was examined. Photographs and dimensions of the engine and the engine bay were taken. The large engine powering these vehicles is designed for hauling very heavy loads; thus producing high amplitude sounds, very similar to the sound of a train locomotive. A photo of the engine is shown in Figure 32.

Figure 32 – CAT 785B haul truck engine.
Through inspection, it can be seen that the engine is largely exposed to the exterior through both the wheel wells and the undercarriage. With such a large engine, the shell noise is a significant contributor to environmental noise. This major flaw is illustrated in Figure 33 through Figure 41.

From the images of the 785B mining vehicle with the engine removed, the exposed engine areas are apparent. These areas coincide the problem regions identified through the noise source identification exercise. A fundamental rule of thumb for noise abatement is to apply the abatement near to the source. For this vehicle, there are no interior walls in the engine bay to install noise absorptive material. There is also the concern that interior treatment may result in overheating and performance problems. As such, the application of abatement material is limited to the exterior frame of the vehicle.

Figure 33 – Passenger side front wheel well of 785B mining vehicle with engine removed.
Figure 34 – Front of 785B mining vehicle with engine and front grill removed.

Figure 35 – Front of 785B mining vehicle with engine and front grill removed.
Figure 36 – Driver side engine housing of 785B mining vehicle.

Figure 37 – Passenger side engine housing of 785B mining vehicle.
Figure 38 – Driver side front wheel well from behind front tire of 785B mining vehicle with engine removed.

Figure 39 – Passenger side front wheel well of 785B mining vehicle.
Figure 40 – Passenger side front wheel well from behind front tire of 785B mining vehicle.

Figure 41 – Front undercarriage of 785B mining vehicle.
Given the above limitations, the most viable approach is to install a barrier or curtain to the wheel wells and undercarriage openings of the vehicle to block and absorb the emitting shell noise through these regions. However, the addition of any barrier material is not a simple solution. Acoustic materials were researched with the intent to find a material with high absorption, transmission loss and can withstand the harsh environment to which off road mining vehicles are exposed. Other considerations such as flammability and oil/water resistance must also be taken into account.

Based on a thorough search for abatement material options, a Barymat material was selected for the proposed application. Specifically, Barymat M-600D was selected and is shown in Figure 42. This material is a 0.56-inch thick composite material and is comprised of a deep embossed vinyl wear surface on top of a high transmission loss flexible barrier with a 0.375 inch closed cell modified PVC/nitrile rubber foam-decoupling layer. This material is designed for vehicle floors, firewall barriers, control room floors, and vibration isolation. The Barymat M-600D is also resistant to exposure to water and oil making it ideal for applications inside harsh engine compartments.

Figure 42 – Barymat M-600D.
The Barymat M-600D was applied to the identified sub-source regions in the wheel well and undercarriage of the 785B mining vehicle. This abatement is intended to block/absorb the noise emission from the engine emitted through the identified regions. To accommodate the installation of the Barymat, mounting studs were welded to the vehicle to allow the material to be hung and bolted directly to the vehicle completely covering the openings. To do this, the openings were measured and the material was cut to fit in the front and back of each wheel well and the front portion of the undercarriage directly below the engine. These custom fitted pieces of M-600D material were bolted to the mounting plates welded directly to the vehicle’s frame. Figure 43 through Figure 50 are images of the 785B mining vehicle with the acoustical louvre installed after the installation of the noise abatement material.

Figure 43 – 785B mining vehicle after installation of abatement.
Figure 44 – Passenger side front wheel well from front of front tire of 785B mining vehicle after installation of abatement.

Figure 45 – Passenger side front wheel well from back of front tire of 785B mining vehicle after installation of abatement.
Figure 46 – Driver side front wheel well from front of the front tire of 785B mining vehicle after installation of abatement.

Figure 47 – Driver side front wheel well from the back of the front tire of 785B mining vehicle after installation of abatement.
Figure 48 – Driver side undercarriage of 785B mining vehicle after installation of abatement.

Figure 49 – Front undercarriage of 785B mining vehicle after installation of abatement.
As displayed in the above figures, all openings were covered with the noise blocking material. Upon completion of the installation of the proposed noise abatement, the next step is to re-evaluate the noise emissions from the truck in order to validate the effectiveness of the abatement.

5.2 Analysis of Noise Abatement Measurements

The M-600D Barymat material was installed on the haul truck that has the acoustical louvre in order to validate the proposed noise abatement panels. In order to do so, a repeat of the measurements performed previously on the vehicles was conducted again after the abatement was installed. Due to limited access to the truck, only the stationary NSI measurements were performed along with a few pass-by SPL measurements. The comparison of these measurements to the benchmark results presented in earlier sections of this chapter was used to quantify the impact of the noise abatement treatment.
5.2.1 **Stationary Measurement Comparison and Analysis**

The procedure for the measurements of the Stationary NSI data was detailed in section 4.3. The 60-channel circular array was position at a distance of three metres from the vehicle and the data was processed using the B&K Array Acoustic Post-Processing software with the same calculation setup used for the pass-by measurements. This data was also combined to get one entire vehicle noise map.

The sound intensity maps generated through the post-processing of the raw array data are used to identify the significant noise contributors and re-rank the sub-sources after the installation of the noise abatement material. The re-evaluation of the NSI data provide insight on the impact that the abatement has on the overall noise emission of the 785B vehicle. Although the stationary measurements are not representative of the regular operation of the mining vehicles, they provide better resolution for results and are better capable of quantifying the impact of the installed barrier material. A similar comparison was demonstrated for the acoustical louvre in section 5.1.2. The overall sound intensity map was computed and presented in Figure 51. Figure 51 uses the same sound intensity level scale given in the overall sound intensity level maps in section 5.1.2 to maintain comparability. The same sub-sources are highlighted, but with a lesser sound intensity level as previously found without the noise abatement material.
Figure 51 - A-weighted sound intensity level map for the 785B mining vehicle with acoustical louvre and installed abatement material.

The individual isolated sound intensity maps are given in Appendix C (C 1 through C 8). These sound intensity maps and sound power level plots were used to quantify each significant sub-source for comparison with the benchmarked noise performance of the 785B with the acoustical louvre presented in section 5.1.2. The comparison of the data for the case with the abatement are given in Table 13 through Table 16.
Table 13 – Overall sound power levels for each section of the front grill of the 785B vehicle stationary measurements with and without the additional abatement (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Abatement (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Passenger Lower</td>
<td>110</td>
<td>109</td>
<td>1</td>
</tr>
<tr>
<td>Front Passenger Upper</td>
<td>108</td>
<td>108</td>
<td>0</td>
</tr>
<tr>
<td>Front Driver Upper</td>
<td>109</td>
<td>109</td>
<td>0</td>
</tr>
<tr>
<td>Front Driver Lower</td>
<td>111</td>
<td>112</td>
<td>-1</td>
</tr>
<tr>
<td>Average</td>
<td>109.5</td>
<td>109.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 14 – Overall sound power levels for each section of the 785B vehicle sides stationary measurements with and without the additional abatement (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Abatement (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver Front Upper</td>
<td>105</td>
<td>104</td>
<td>1</td>
</tr>
<tr>
<td>Passenger Front Upper</td>
<td>112</td>
<td>109</td>
<td>3</td>
</tr>
<tr>
<td>Passenger Front Lower</td>
<td>111</td>
<td>109</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 15 – Isolated source sound power levels for each section of the front grill of the 785B vehicle stationary measurements with and without the additional abatement (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Abatement (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Passenger Lower</td>
<td>104</td>
<td>103</td>
<td>1</td>
</tr>
<tr>
<td>Front Passenger Upper</td>
<td>102</td>
<td>102</td>
<td>0</td>
</tr>
<tr>
<td>Front Driver Upper</td>
<td>101</td>
<td>104</td>
<td>-3</td>
</tr>
<tr>
<td>Front Driver Lower</td>
<td>107</td>
<td>107</td>
<td>0</td>
</tr>
<tr>
<td>Average</td>
<td>103.5</td>
<td>104</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
Table 16 – Isolated source sound power levels for each section of the 785B vehicle sides stationary measurements with and without the additional abatement (A-weighted).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Isolated Region</th>
<th>Louvre (dB(A)/1p W)</th>
<th>Abatement (dB(A)/1p W)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver Front Upper</td>
<td>Wheel Well</td>
<td>99</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>Passenger Front Upper</td>
<td>Exhaust</td>
<td>103</td>
<td>99</td>
<td>4</td>
</tr>
<tr>
<td>Passenger Front Upper</td>
<td>Wheel Well</td>
<td>104</td>
<td>103</td>
<td>1</td>
</tr>
<tr>
<td>Passenger Front Lower</td>
<td>Wheel Well</td>
<td>106</td>
<td>103</td>
<td>3</td>
</tr>
</tbody>
</table>

For both Table 13 and Table 15, it is apparent that there exists no reduction in the front grill for both the overall and isolated sound power level. This is an expected result since there was no addition of abatement material to the front of the vehicle. Thus, the sound power level from the front of the vehicle remained the same. In Table 14 and Table 16, the level was observed to have a reduction in the range of 1 to 3 dB for the entire side of the vehicle and 0 to 4 dB for the isolated measurements. In the previous measurements, it is observed that the reductions for the pass-by measurements are greater than that of the stationary measurement; thus, it can be assumed that a reduction of 3 dB correlates to a greater reduction in regular operation where the engine is under load. The sound power level reductions for the stationary NSI results illustrates promise for the Barymat M-600D as a viable option to be a viable noise abatement treatment.

With the abatement material and acoustic louver installed, it can be said that the same amount of acoustical energy is still created by the engine’s noise mechanisms. Since both these abatement treatments have some absorptive noise control characteristics, some of the acoustic energy emitted from the truck is reduced, and not just blocked, as shown in the sound power level reductions presented above.
For re-ranking of the identified sub-sources in the 785B with the abatement material installed, only the sources on the sides of the vehicle are displayed since the abatement material has no effect on the front of the vehicle given that no material was applied to the front of the vehicle.

Table 17 – Ranking of isolated noise contributors identified on the 785B haul trucks with and without abatement material using the stationary measurement NSI results (A-weighted).

<table>
<thead>
<tr>
<th>Vehicle Side</th>
<th>Noise Contributors</th>
<th>Abatement dB(A)/1p W</th>
<th>Rank</th>
<th>Louvre dB(A)/1p W</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>Wheel Well</td>
<td>99</td>
<td>3</td>
<td>99</td>
<td>4</td>
</tr>
<tr>
<td>Passenger</td>
<td>Exhaust</td>
<td>99</td>
<td>3</td>
<td>103</td>
<td>3</td>
</tr>
<tr>
<td>Passenger</td>
<td>Wheel Well</td>
<td>103</td>
<td>2</td>
<td>106</td>
<td>1</td>
</tr>
<tr>
<td>Front</td>
<td>Front Grill</td>
<td>104</td>
<td>1</td>
<td>104</td>
<td>2</td>
</tr>
</tbody>
</table>

In Table 17, it is shown that for the case with the abatement, the front grill now becomes the most significant sub-source without an increase in the sound power emitted from the front grill. This implies that the reduction in sound power level provided by the installation of the M-600D abatement material is sufficient in reducing the emissions of the abated sub-sources relative to other noise contributors.

5.2.2 Pass-by SPL Comparison

The outcomes of the analysis of the abated truck show great promise, but these outcomes do not necessarily speak to the expected perceived loudness of the vehicle at a distance. It is observed that the abated truck sounded to be significantly quieter at large distances when compared to the trucks without the abatement material.
Single channel pass-by recordings of the vehicle with the abatement were acquired to compare to the pass-by recordings of the vehicle without the abatement. The signals were processed using B&K Reflex to compute the 1/3-octave CPB SPL data. This process chain is the similar to the one detailed in Figure 31 without the A-weighting pre-analysis. A simple comparison of the SPLs at an equivalent distance was made to show an insignificant relation. To uncover the reason for the perceived reduction in loudness at distances, the 1/3-octave sound power levels were compared. To do this, the sound pressure levels were converted to sound power level and then compared.

It is apparent from Table 18 that the absorption material provides good reduction in the low to mid frequencies, but has lesser performance at the high frequencies. This lesser performance in the high frequencies can be attributed to new noise emissions generated at small gaps in the application of the barrier material and induced vibration of the Barymat material. However, when considering the propagation of sound over large distances, the low frequency content of sound will propagate further than the high frequency sounds. That is, the atmosphere more easily absorbs the high frequency content of sound. To model this, a simulation using B&K Predictor with the calculated sound power levels was developed to predict the SPL at a distance similar to the distance between the haul road and the nearby residential receptors. For the GoldCorp mines, the nearest sensitive receptors are 700 metres from the haul roads. As such, this distance was used for the model to predict the 1/3-octave SPLs at the receptor.

Table 19 presents the SPLs for the truck with and without the abatement installed. Reductions are realized for both the day and night receptor heights of 1.5 m and 4.5 m respectively, as set by the MOE. At both heights, there is an overall SPL reduction of 3 dB.
at the representative receptor. In addition, it was observed that the abatement material provides the best noise control in the low to mid frequency range, with poor performance in the high frequencies. For the high frequencies, the abatement actually performs worse than the truck without the abatement; but it is important to note that the SPLs in the high frequency are so low such that they are not perceivable. However, this does not matter much since the atmosphere will attenuate the high frequency sounds by the time they reach the far away residential receptors. Thus, it is shown that the addition of the abatement treatments aids in the reduction of low frequency content, which for this application provides a worthy reduction in SPL at the receptors.
Table 18 – Comparison of 1/3-octave sound power levels from pass-by measurements.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>$L_W$ with Abatement (dB)</th>
<th>$L_W$ without Abatement (dB)</th>
<th>Reduction (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>103.2</td>
<td>124.3</td>
<td>21.0</td>
</tr>
<tr>
<td>25</td>
<td>115.5</td>
<td>124.8</td>
<td>9.3</td>
</tr>
<tr>
<td>31.5</td>
<td>116.0</td>
<td>122.8</td>
<td>6.8</td>
</tr>
<tr>
<td>40</td>
<td>119.6</td>
<td>116.9</td>
<td>-2.7</td>
</tr>
<tr>
<td>50</td>
<td>118.2</td>
<td>120.0</td>
<td>1.8</td>
</tr>
<tr>
<td>63</td>
<td>122.6</td>
<td>117.8</td>
<td>-4.8</td>
</tr>
<tr>
<td>80</td>
<td>123.5</td>
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Table 19 – Calculated SPL 700 m from a 785B mining haul truck with and without abatement at a receptor of height 1.5 m and 4.5 m (A-weighted).

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5.2.3 Noise Abatement Validation

For the GoldCorp mines, the interest in noise emission reduction of the 785B mining vehicle was to allow the mine to operate within compliance of the MOE’s environment noise emission guidelines. In order to comply with these MOE guidelines, it is often a matter of a very small reduction in sound level. Thus, for large companies such as GoldCorp, the reduction of noise emissions can be the deciding factor to allow the continuation of operations.

As presented in this section, the addition of the Barymat M-600D barrier material to the wheel wells and undercarriage of the vehicles provided a 3 dB reduction in overall SPL at a receptor located 700 m from the haul road. A reduction of this magnitude to every haul road vehicle in GoldCorp fleets will mean compliance with the MOE guidelines and continued operation at full capacity. From this standpoint, the realized reductions from the addition of the suggested abatement are significant. It is recommended that the Barymat M-600D material be installed on the wheel wells and undercarriage as an effective noise abatement treatment in the control of engine shell noise.
VI. Recommendations and Conclusions

6.1 Conclusions

The motivation for this research was to develop a customized and effective noise abatement plan for the fleet of 785B mining vehicles. It was also the intent to use advanced tools and analysis techniques, which are not normally used for this specific application. From the presented results, a thorough understanding of the noise mechanisms for the haul truck and their relative ranking was achieved. Using this information, an effective abatement plan including the design and subsequent testing proved to be effective and relatively inexpensive to implement, compared to more complex noise control measures such as the installation of a several kilometer noise barrier wall.

Previously, GoldCorp has attempted various noise abatement treatments without any conclusive data concerning the effectiveness of these treatments. This research has quantified the effectiveness of treatments, both previously installed as well as newly suggested. Advanced NSI analysis was the pinnacle of the investigation and design of the noise abatement treatment for this research. The novelty is the application of new and advanced algorithms for the noise source investigation and subsequent analysis of the outcome of the abatement. Through the use of NSI, significant sub-sources were identified and their impacts were measured allowing for the resulting abatement design.

NSI identified the front grill, front wheel wells, exhaust and undercarriage as the dominant noise contributors to the overall noise emission of the 785B mining vehicle. The sources were ranked with the front grill having the least impact relative to the other sub-
sources; thus, identifying the wheel wells, undercarriage and exhaust as the target for noise abatement.

Previously, custom exhaust silencers from Silex Inc. were installed on the entire 785B fleet at GoldCorp. The testing detailed in this thesis concluded that for under the test conditions the silencer was not very effective in abating the exhaust noise. As this option had already been thoroughly explored, focus was directed to the other sources. In addition, one of the 785B in the fleet was fitted with an acoustical louvre to reduce the noise emissions from the front grill. Through NSI analysis, it was determined that this acoustical louvre provided significant reduction in the sound power level from the front of the vehicle. For the pass-by NSI results, the acoustical louvre provided a 9 dB reduction, a value that is perceived as nearly half as loud.

Upon review of the 1/3\textsuperscript{rd} octave sound power spectra, and modelling the proposed attenuation of various abatement materials, application of the barrier material Barymat M-600D was recommended for the wheel wells and undercarriage of the mining vehicle. Due to airflow and overheating concerns, it was not feasible to apply an abatement treatment in the engine housing or directly to the engine; instead, the barrier material was fixed to the exterior of the vehicle in the wheel wells and undercarriage to lessen the noise emissions from these areas.

After the installation of the Barymat material, the stationary NSI measurements were repeated along with sound pressure level pass-by measurements using a sound level meter. The NSI measurements showed a small reduction in sound power level for the regions where the abatement was applied. These small reductions were hardly perceivable
when in close proximity to the vehicle, but at greater distances, it was observed that the vehicle with the abatement was significantly quieter in comparison to the vehicles without the barrier material installed. In order to quantify this observation, additional analysis was undertaken. The sound power level was calculated using a single channel SPL measurement for the same vehicle, with and without the noise abatement. Using B&K Predictor, an acoustical propagation model was performed for a stationary vehicle as the source and a receptor located 700 m from the source. The simulation was computed twice using the 1/3-octave sound power level of the vehicle; once with the abatement and a second time with the levels for the unabated vehicle. An overall reduction of 3 dB was predicted at the receptors having heights of 1.5 m and 4.5 m. The propagation model followed the methodologies prescribed by ISO 9614-2, and recommended by the MOE for the prediction of noise levels at an outdoor reception area and the plane of a second storey window. For GoldCorp, this was considered to be a significant improvement in the operations, and one which in many cases will allow them to operate within compliance of the MOE guidelines, which otherwise, they would not.

6.2 Recommendations

The results in this thesis conclude that the recommended and tested abatement is a viable option for implementation on the 785B mining vehicles. It was proven to effectively reduce the noise emissions by a level that will allow GoldCorp to operate within the required MOE guidelines, in most circumstances. Further, the acoustical louvre previously installed on one vehicle was validated and found to provide a reduction of 9 dB under frontal test conditions. Conversely, the exhaust silencer was not found to be as effective in reducing the noise emission of the truck.
In conclusion, it is recommended that all vehicles be fitted with the proposed acoustical louvre and the barrier panels comprised of Barymat M-600D in the front wheel wells as well as the undercarriage of the 785B haul truck. With this abatement treatment, noise control is possible for this complex and challenging problem.

6.3 Future Work

Although the completed research provided an effective noise abatement plan for the 785B mining vehicles, continued research in the design and validation of a more advanced noise abatement treatment is possible and recommended.

The exhaust of the vehicle remains to be a significant noise contributor to the overall emissions of the 785B mining vehicle. It was shown that the installed aftermarket silencer did not result in effective noise control. Retesting of the silencer on a different vehicle would be beneficial to determine whether the instance tested was an outlier. Additionally, research in other noise control options for the exhaust would provide insight on alternative noise abatement treatments for this application.

The acoustical louvre was shown to have a significant impact on the noise control of the 785B mining vehicle. A further investigation on the installation of the acoustical louvre and any improvements would be helpful to achieve additional positive acoustical results. It was observed that the installed louvre did not completely cover the bottom section of the front grill, allowing some noise to escape. This was due to interference from the headlights embedded in the front grill, which prevented the louvre from being optimally installed. It is recommended that for future installations of the louvre that the lights be relocated forward allowing the louvre to better cover the front grill and absorb the frontal noise.
noise. Further, the louvre was an off the shelf unit design for installation into the side of buildings to control the noise of compressor rooms and emergency generators. For this application, additional research in the design of a custom louvre for the haul truck abatement may provide additional benefit and is recommended.

Finally, even though the M-600D was shown to provide effective noise abatement for this application, future research into other materials or composites of two or more barriers is recommended. The Barymat material provided good acoustical performance, while also having the other necessary physical properties required for the application; alternative materials may also exist. Alternatively, the design of a custom composite may also warrant consideration.

Consideration of these future research ideas for the noise abatement of the 785B mining vehicles may provide a next level noise abatement design. This would not only better allow companies like GoldCorp to operate in more noise sensitive environments, but would give the manufacturers of these heavy and highly specialized industrial equipment the opportunity to offer high end noise control packages with their product.
Appendices

Appendix A: Pass-by NSI Results

A 1: A-weighted sound intensity level noise map from the driver’s side of the 785B mining haul truck with aftermarket acoustical louvre.

A 2: A-weighted sound intensity level noise map from the exhaust side of the 785B mining haul truck with aftermarket acoustical louvre.
A 3: A-weighted sound intensity level noise map from the head-on perspective of the 785B mining haul truck with aftermarket acoustical louvre.

A 4: A-weighted sound intensity level noise map from the driver’s side of the 785B mining haul truck without the aftermarket acoustical louvre.
A 5: A-weighted sound intensity level noise map from the exhaust side of the 785B mining haul truck without the aftermarket acoustical louvre.

A 6: A-weighted sound intensity level noise map from the head-on perspective of the 785B mining haul truck without the aftermarket acoustical louvre.
A 7: Isolated A-weighted sound intensity level noise map from the driver’s side of the 785B mining haul truck with aftermarket acoustical louvre.

A 8: Isolated A-weighted sound intensity level noise map from the driver’s side of the 785B mining haul truck without the aftermarket acoustical louvre.
A 9: Isolated A-weighted sound intensity level noise map from the exhaust side of the 785B mining haul truck with aftermarket acoustical louvre.

A 10: Isolated A-weighted sound intensity level noise map from the exhaust side of the 785B mining haul truck without the aftermarket acoustical louvre.
A 11: Isolated A-weighted sound intensity level noise map from the head-on perspective of the 785B mining haul truck with aftermarket acoustical louvre.

A 12: Isolated A-weighted sound intensity level noise map from the head-on perspective of the 785B mining haul truck without the aftermarket acoustical louvre.
Appendix B: Stationary NSI Results

B 1: Isolated A-weighted stationary sound intensity level noise map of the lower front passenger side of the 785B mining haul truck with aftermarket acoustical louvre.

B 2: Isolated A-weighted stationary sound intensity level noise map of the upper front passenger side of the 785B mining haul truck with aftermarket acoustical louvre.
B 3: Isolated A-weighted stationary sound intensity level noise map of the lower front driver side of the 785B mining haul truck with aftermarket acoustical louvre.

B 4: Isolated A-weighted stationary sound intensity level noise map of the upper front driver side of the 785B mining haul truck with aftermarket acoustical louvre.
B 5: Isolated A-weighted stationary sound intensity level noise map of the upper driver side front of the 785B mining haul truck with aftermarket acoustical louvre.

B 6: Isolated A-weighted stationary sound intensity level noise map of the upper passenger side front of the 785B mining haul truck with aftermarket acoustical louvre.
B 7: Isolated A-weighted stationary sound intensity level noise map of the lower passenger side front of the 785B mining haul truck with aftermarket acoustical louvre.

B 8: Isolated A-weighted stationary sound intensity level noise map of the lower front passenger side of the 785B mining haul truck without the aftermarket acoustical louvre.
B 9: Isolated A-weighted stationary sound intensity level noise map of the upper front passenger side of the 785B mining haul truck without the aftermarket acoustical louvre.

B 10: Isolated A-weighted stationary sound intensity level noise map of the lower front driver side of the 785B mining haul truck without the aftermarket acoustical louvre.
B 11: Isolated A-weighted stationary sound intensity level noise map of the upper front driver side of the 785B mining haul truck without the aftermarket acoustical louvre.

B 12: Isolated A-weighted stationary sound intensity level noise map of the upper driver side front of the 785B mining haul truck without the aftermarket acoustical louvre.
B 13: Isolated A-weighted stationary sound intensity level noise map of the lower driver side front of the 785B mining haul truck without the aftermarket acoustical louvre.

B 14: Isolated A-weighted stationary sound intensity level noise map of the upper passenger side front of the 785B mining haul truck without the aftermarket acoustical louvre.
B 15: Isolated A-weighted stationary sound intensity level noise map of the lower passenger side front of the 785B mining haul truck without the aftermarket acoustical louvre.

B 16: Isolated A-weighted stationary sound intensity level noise map of the upper passenger side middle of the 785B mining haul truck without the aftermarket acoustical louvre.
B 17: Isolated A-weighted stationary sound intensity level noise map of the lower passenger side middle of the 785B mining haul truck without the aftermarket acoustical louvre.
Appendix C: Stationary Noise Abatement NSI Results

C 1: Isolated A-weighted stationary sound intensity level noise map of the lower front passenger side of the 785B mining haul truck after the installation of noise abatement material.

C 2: Isolated A-weighted stationary sound intensity level noise map of the upper front passenger side of the 785B mining haul truck after the installation of noise abatement material.
C 3: Isolated A-weighted stationary sound intensity level noise map of the upper front driver side of the 785B mining haul truck after the installation of noise abatement material.

C 4: Isolated A-weighted stationary sound intensity level noise map of the lower front driver side of the 785B mining haul truck after the installation of noise abatement material.
C 5: Isolated A-weighted stationary sound intensity level noise map of the lower driver side front of the 785B mining haul truck after the installation of noise abatement material.

C 6: Isolated A-weighted stationary sound intensity level noise map of the upper driver side front of the 785B mining haul truck after the installation of noise abatement material.
C 7: Isolated A-weighted stationary sound intensity level noise map of the upper passenger side front of the 785B mining haul truck after the installation of noise abatement material.

C 8: Isolated A-weighted stationary sound intensity level noise map of the lower passenger side front of the 785B mining haul truck after the installation of noise abatement material.
REFERENCES/BIBLIOGRAPHY


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