Assessing the accuracy of directional real-time noise monitoring systems

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ABSTRACT

Current and proposed open cut mines are usually required via their approval to install real-time noise monitoring systems (NMS) as a management tool. In cases where multiple open-cut mines exist in close proximity to noise sensitive receptors, directional noise-monitoring systems (DNMS) are used in order to determine individual contributions from each mine/noise source. However, little independent testing exists comparing the various DNMS available in the market. As NMS are a regulatory requirement, the focus of this study is testing the effectiveness of three DNMS currently being utilised at open cut mines in NSW at accurately determining the direction and contribution of multiple noise sources in controlled scenarios.

1. INTRODUCTION

DNMS were innovated in Australia in response to growing expectations from communities and regulators that industrial operations actively manage their noise impacts on the surrounding environment. Existing NMS were already capable of measuring the overall acoustic environment in real-time, but were unable to differentiate contributions from, or directions of, individual noise sources. Where multiple sources of industrial noise existed, it became necessary to accurately determine contributions from each source, individually, in real-time in order to manage their contribution to the cumulative noise impact. Subsequently, DNMS were conceived and designed as a management tool to differentiate contributions from industrial noise sources (such as mines, factories, workshops, or power stations) from each other as well as from other extraneous noise (such as traffic or other ambient noise).

Real-time NMS results have been validated extensively, at the request of both clients and regulators, by performing attended monitoring at the same location as the NMS and comparing results. These validation exercises have generally found that:

- Omnidirectional NMS accurately measure the overall acoustic environment;
- DNMS accurately measure the overall acoustic environment;
- DNMS determine noise contributions and directions reasonably accurately when there is one primary noise source; and
- DNMS often do not determine noise contributions and directions correctly when there are multiple primary noise sources and/or secondary noise sources.

These findings have been reinforced by the existing research discussed below, other validation surveys, and, anecdotally, by other environmental consultants, vendors, and mines. NMS are a regulatory requirement for many mining operations. As DNMS are used to fulfil this requirement, it is important to establish how effectively these work in the field for practical applications.

The purpose of this paper is to evaluate the capabilities and limitations of three commonly used DNMS, referred to as Units A, B and C. Various mines in NSW were approached, under the condition of anonymity, to test their DNMS for this research. Many of these mines exist in relatively close proximity in the context of environmental noise levels (still 2-5 kilometres) to sensitive receptors and rely on DNMS as a primary noise management tool, both for managing noise levels generated by site and investigating noise complaints. The tests described in this paper were conducted using electronically generated sound. The test signals were not based on mining noise and the results reported do not include mining data.

2. EXISTING RESEARCH

A paper by Rob Bullen published at the Australian Acoustical Society conference in 2001, 'A System for Automatically Detecting the Direction and Level of Noise Sources', tested a DNMS with one to two reference noise sources. Findings from testing were that:

> *The system described in this paper provides a means of automatically assigning measured L_{Aeq} noise levels to sources located in specific directions. If one source is dominant during a 1-second sample, the level and direction of that source will be accurately recorded to within about 1dBA and 10^o respectively. Sources which are not dominant will also be detected, but more care needs to be exercised in estimating their level, and in some cases it may be necessary to quote a range of possible noise levels.* (Bullen, 2001:4).

Determining the contributions of non-dominant noise sources is important in cases where noise impacts from multiple industrial sources must be managed individually. Due to difference in the size of operations or meteorological enhancement, one noise source is often dominant while the other is secondary. However, the impacts of both operations must be determined in order to inform effective management.

A subsequent paper by Bullen and Lawrence presented at the 14th International Congress on Sound & Vibration (2007), 'Measured Performance of a Directional Noise Monitoring System' showed that secondary sources could be effectively determined below ambient noise levels in many situations. However, it also noted that:

> *As the noise level of the signal to be detected becomes lower compared with the ambient noise, at some point the cross-correlation maxima associated with the source are lost among small random maxima in the cross-correlation function for the remaining noise. If the ambient noise contains a strong signal from another source, particularly a low-frequency source, the resulting large broad maxima in the cross-correlation function have a greater chance of obscuring maxima associated with a weaker second source.* (Bullen & Lawrence, 2007:3)

This is relevant to mining operations which may impact sensitive receivers many kilometres away, and due to differential attenuation, usually only at frequencies equal to or less than 1000 Hz. Therefore, this survey attempts to investigate the underestimating of secondary noise sources, especially in lower frequencies, and determine whether this is a limitation of other DNMS.

3. METHODOLOGY

Three reference noise sources (RNS) were used to generate consistent and controllable test conditions in the field. Self-powered speakers were set up at an equal distance (approximately 10 metres) but at varying angles around the DNMS, and generated pink noise. A Type 1 sound level meter (SLM) was used in the field to ensure RNS were generating reference noise levels, and also to validate overall noise levels reported by the DNMS. Reference noise levels were measured individually at the DNMS before and after testing to confirm that each RNS was generating equal acoustic energy within 1 dB(A). Therefore, a testing error of + or – 1 dB(A) is assumed in the results provided.

Due to the short distance between RNS and DNMS, meteorological effects have not been considered. As RNS were equal distance from DNMS and ground conditions were uniform, ground reflection and differential ground absorption have also not been considered.

Background noise levels were noted, before and after testing, and RNS were configured to generate noise levels that were at least 25 dB(A) above ambient L_{Aeq} levels and at least 10 dB(A) above ambient L_{Amax} levels to prevent contributions from non-reference sources in the environment. While all effort was taken to prevent contributions from non-reference sources, it is possible that noise events near the DNMS (such as passing birds) could affect measured noise levels. DNMS were tested in the field under normal operating conditions at average wind speeds of less than 3 metres per second.

All three DNMS collect and report 15-minute data summaries to the respective mine. Each testing scenario described below was conducted for a duration of 15 minutes to correspond with the data processing of the DNMS. In some cases, data additional to the 15-minute summaries were available from the manufacturer or respective mine, and have been used for analysis.

All three DNMS also collect and sum directional noise data within specified ranges of angles corresponding with nearby mines that are likely to contribute to the acoustic environment. These are referred to as "Areas of Interest" (AOI). AOI were preconfigured within Unit A and B, therefore two of the three reference noise sources were placed within existing AOI and a third RNS was placed outside any AOI to represent other possible noise sources (e.g. traffic, tractors, pumps, etc.). Due to the way Unit C processes directional data, this method was changed slightly to calculate three AOI of different sizes, each containing a RNS. RNS were placed away from AOI boundaries in all tests. A representative example of AOI (for Unit A) is shown in Figure 1. Please note that all figures containing AOI in this document are representative only and have been altered to protect the identity of participants. The orientation and placement of AOI have been changed and figures do not show cardinal directions for this reason.

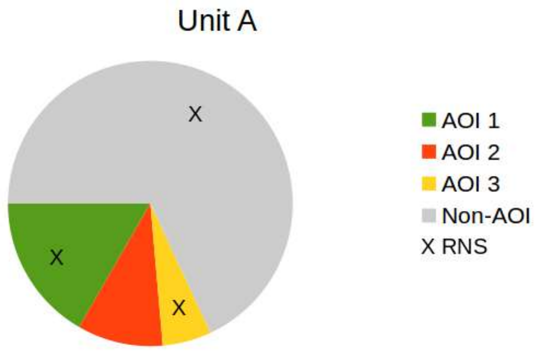

Figure 1 - Unit A AOI

Due to differential attenuation primarily caused by atmospheric absorption, mining noise is typically experienced in lower frequencies at affected receptors. As each unit had different methods of assessing low-pass noise, predicted results were calculated from the overall low-pass L_{Aeq} provided by the instrument, which was assumed to be accurate. The cut-off frequency for each unit is provided in Section 4.

Four scenarios were developed to test the DNMS ability to determine the directions and contributions of steady-state, intermittent, and gradually changing noise sources. Further detail of each scenario is provided below.

3.1 Scenario 1

All three RNS generated steady-state pink noise at the same levels

. This was to test the ability of the DNMS to determine directions and contributions of noise sources when there was no primary/dominant noise source. This represents a real-world situation occasionally encountered during attended monitoring where two (or more) sources are generating very similar levels of continuous noise at similar frequencies.

3.2 Scenario 2

Each RNS generated steady-state pink noise, but at different levels. The loudest RNS generated pink noise that was 3 dB above the secondary RNS and 6 dB above the tertiary RNS. This represents a real-world situation often encountered during attended monitoring where one source is dominant over another, but the contributions of both must be determined.

3.3 Scenario 3

Each RNS generated steady-state pink noise for 1 minute and 30 seconds and then generated no noise for 1 minute and 30 seconds, as shown in Figure 2. These events are staggered so that at least one speaker was always generating noise above the ambient level, however over the course of the 15-minute measurement all three RNS generated the same noise contribution (acoustic energy). This scenario represents periodic noise events that may occur in the environment.

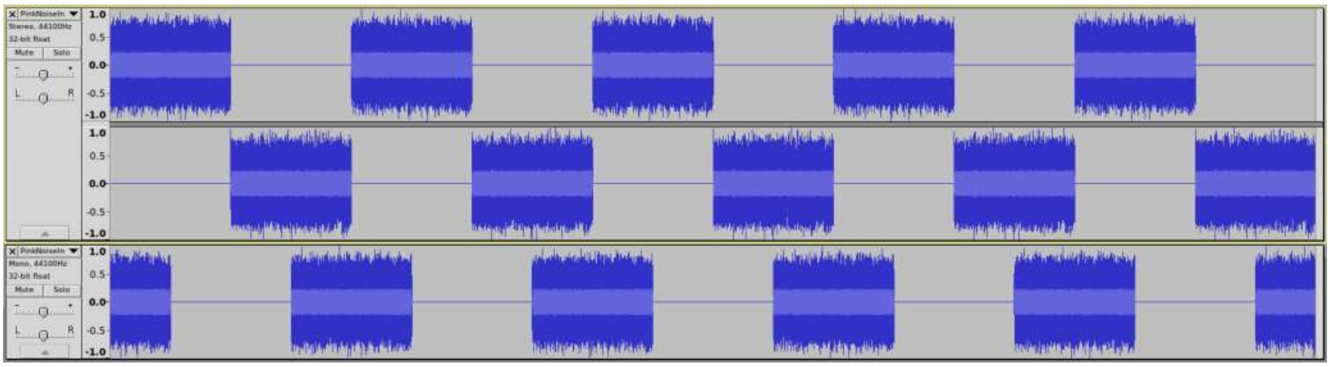

Figure 2 - Scenario 3 Test Condition

3.4 Scenario 4

Each RNS generated pink noise that gradually increased to a maximum and then decreased to zero on a 3 minute cycle, as shown in Figure 3. These cycles were staggered so that at least one speaker was always generating significant noise above the ambient level, however over the course of the 15-minute measurement all three RNS generated the same noise contribution (acoustic energy). This scenario represents gradual noise events that may occur in the environment.

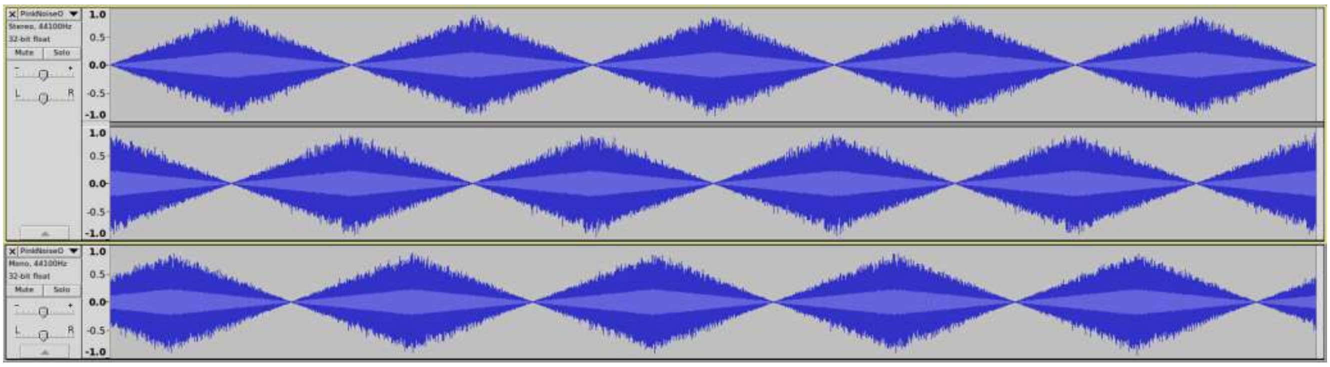

Figure 3 - Scenario 4 Test Conditions

4. UNIT SPECIFICIATIONS

4.1 Unit A

Unit A includes three microphones arranged in a triangular array. Directional raw data from Unit A, including both all-pass and low-pass to 1000 Hz data, were available in 5-minute intervals and used to create 15-minute summaries. Both AP and LP results have been provided. The included angle of AOI 1 was 60 degrees, AOI 2 was 35 degrees, and AOI 3 was 20 degrees. The non-AOI angles totalled 245 degrees. Figure 1 (above) shows a graphical representation of AOI for Unit A.

4.2 Unit B

Unit B includes five microphones arranged in a pyramidal array. Low-pass directional data to 630 Hz were available in intervals varying from 6 to 31 seconds, in addition to 15-minute summaries. Directional all-pass data were not available.

This unit was tested twice. During the first test, the unit was unable to produce directional data for Scenario 1 and only produced approximately 15 seconds of directional data for Scenario 2. Scenarios 3 and 4 ran for the full duration. The unit was subsequently relocated and an attempt was made to retest the unit at its new location, two months later. During the second test, the unit only provided approximately 15 seconds of directional data for Scenario 1. Remaining scenarios ran for the full duration. In both instances, the monitor continued generating omnidirectional statistics. The 15-second results have been provided, as both of these scenarios are steady-state tests.

During the first test, AOI 1 was approximately 45 degrees, AOI 2 was approximately 95 degrees, and the non-AOI included angles totalled approximately 220 degrees. During the second test, AOI 1 was approximately 45 degrees, AOI 2 was approximately 40 degrees, and the non-AOI included angles totalled approximately 275 degrees. RNS were placed away from AOI boundaries. Figure 4 shows graphical representation of AOI for both tests.

Results from both tests have been provided.

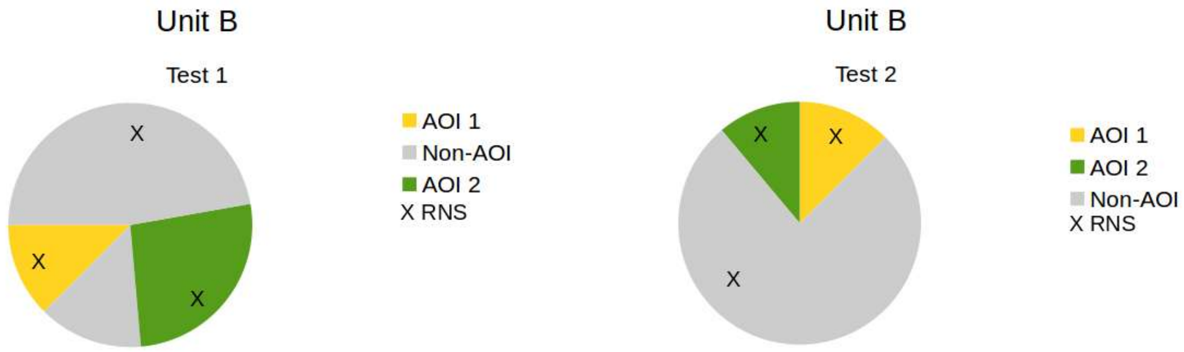

Figure 4 – Unit B AOI

4.3 Unit C

Unit C includes twenty-six microphones arranged in a pentangular array. Low-pass directional data from approximately 100 to 630 Hz were provided by Unit C in 15-minute intervals, from which custom AOI were calculated. Using the raw data, two sets of AOI were calculated to highlight differences in contributions when the size of an AOI is increased or decreased. This is discussed further in Section 5.

5. RESULTS

Results for Scenarios 1, 3, and 4 are expected to have equal contributions from two AOI and the non−AOI containing RNS. Scenario 2 is expected to have a primary, secondary, and tertiary contribution from two AOI and the non-AOI, each separated by 3 dB.

5.1 Unit A

Table 1: Total measured noise levels, dB

Test Scenario	SLM Total L_{Aeq}	Unit A Total L_{Aeq}	Difference
1	76.9	77.8	0.9
2	74.8	76.0	1.2
3	74.0	74.9	0.9
4	71.5	72.3	0.8

Table 2: Directional noise levels – all-pass, dB

Test Scenario	Unit A All-Pass L_{Aeq}	AOI 1 All-Pass L_{Aeq}	AOI 2 All-Pass L_{Aeq}	AOI 3 All-Pass L_{Aeq}	Non-AOI All-Pass L_{Aeq}	Predicted L_{Aeq}	Maximum Variance[1]
1	77.8	73.7	53.7	72.7	71.7	73.0	1.3
2	76.0	73.8	-[2]	69.9	66.4	73.6/70.6/67.6	1.2
3	74.9	70.9	64.2	68.8	66.0	70.1	4.1
4	72.3	66.8	63.9	65.9	66.8	67.5	1.6

Notes: 1: AOI 2 did not contain a RNS and has not been compared in variance calculations; and
2: AOI 2 did not produce any contributions during this test.

Table 3: Directional noise levels – low-pass, dB

Test Scenario	Unit A Low-Pass L_{Aeq}	AOI 1 Low-Pass L_{Aeq}	AOI 2 Low-Pass L_{Aeq}	AOI 3 Low-Pass L_{Aeq}	Non-AOI Low-Pass L_{Aeq}	Predicted L_{Aeq}	Maximum Variance[1]
1	70.4	65.0	43.3	62.8	46.1	65.6	19.5
2	68.8	66.2	-[2]	34.6	46.7	66.4/63.4/60.4	28.8
3	67.5	63.6	-[2]	63.0	56.9	62.7	5.8
4	64.9	58.7	46.8	60.2	55.7	60.1	4.4

Notes: 1: AOI 2 did not contain a RNS and has not been compared in variance calculations; and
2: AOI 2 did not produce any contributions during this test.

5.2 Unit B

Table 4: Total measured noise levels, dB (18 May 2016)

Test Scenario	SLM Total L_{Aeq}	Unit B Total L_{Aeq}	Difference
1	87.8	88.2	0.4
2	84.9	85.9	1.0
3	83.8	84.8	1.0
4	82.0	83.0	1.0

Table 5: Directional noise levels – low-pass, dB (18 May 2016)

Test Scenario	Unit B Low-Pass L_{Aeq}	AOI 1 Low-Pass L_{Aeq}	AOI 2 Low-pass L_{Aeq}	Non-AOI Low-Pass L_{Aeq}	Predicted L_{Aeq}	Maximum Variance
1[1]	80.0	-	-	-	-	-
2[2]	77.9	70.0	66.4	76.8	69.5/72.5/75.5	6.1
3	76.9	68.2	71.0	74.8	72.1	3.9
4	75.2	67.6	71.0	71.6	70.4	2.8

Notes: 1: Unit did not provide directional noise data during this test; and
2: Results are based on approximately 15 seconds of directional data.

Table 6: Total measured noise levels, dB (28 July 2016)

Test Scenario	SLM Total L_{Aeq}	Unit B Total L_{Aeq}	Difference
1	80.5	79.2	1.3
2	78.3	77.2	1.1
3	76.7	75.6	1.1
4	75.2	74.2	1.0

Table 7: Directional noise levels – low-pass, dB (28 July 2016)

Test Scenario	Unit B Low-Pass L_{Aeq}	AOI 1 Low-Pass L_{Aeq}	AOI 2 Low-pass L_{Aeq}	Non-AOI Low-Pass L_{Aeq}	Predicted L_{Aeq}	Maximum Variance
1[1]	70.2	65.2	44.8	68.5	65.4	20.6
2	68.4	52.5	26.2	67.1	60.0/63.0/66.0	36.8
3	66.6	61.0	54.6	64.8	61.8	7.2
4	65.4	59.0	60.1	62.2	60.6	1.6

Notes: 1: Results are based on approximately 15 seconds of directional data.

5.3 Unit C

Table 8: Total measured noise levels, dB

Test Scenario	SLM Total L_{Aeq}	Unit C Total L_{Aeq}	Difference
1	88.5	89.9	1.4
2	86.7	87.8	1.1
3	84.8	86.2	1.4
4	83.9	85.1	1.2

In the first set of directional calculations, AOI 1 was approximately 40 degrees, AOI 2 was approximately 60 degrees, and AOI 3 was approximately 20 degrees, as shown in Figure 5.

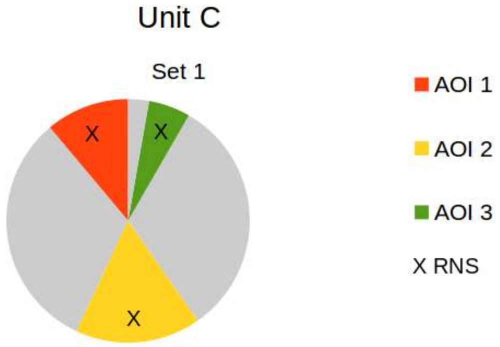

Figure 5 - Unit C, AOI Set 1

Table 9: Directional noise levels – low-pass, dB

Test Scenario	Unit C Low-Pass L_{Aeq}	AOI 1 Low-Pass L_{Aeq}	AOI 2 Low-pass L_{Aeq}	AOI 3 Low-Pass L_{Aeq}	Predicted L_{Aeq}	Maximum Variance
1	85.4	79.4	79.6	78.6	80.6	2.0
2	83.9	77.8	76.9	78.0	78.5/75.5/81.5	3.5
3	82.0	76.9	75.6	75.2	77.2	2.0
4	71.3	76.4	74.7	74.4	76.5	2.1

In the second set of directional calculations, AOI 1 was approximately 40 degrees, AOI 2 was approximately 20 degrees, and AOI 3 was approximately 60 degrees, as shown in Figure 6.

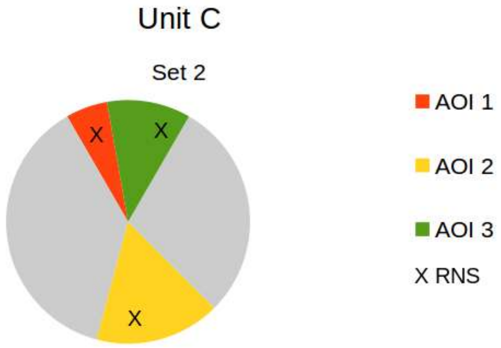

Figure 6 - Unit C, AOI Set 2

Table 10: Directional noise levels – low-pass, dB

Test Scenario	Unit C Low-Pass L_{Aeq}	AOI 1 Low-Pass L_{Aeq}	AOI 2 Low-pass L_{Aeq}	AOI 3 Low-Pass L_{Aeq}	Predicted L_{Aeq}	Maximum Variance
1	85.4	79.4	78.4	79.8	80.6	2.2
2	83.9	77.8	75.1	78.6	78.5/75.5/81.5	2.9
3	82.0	76.9	74.1	76.0	77.2	3.1
4	81.3	76.4	73.1	75.3	76.5	3.4

6. DISCUSSION

As expected, all three DNMS measured the overall acoustic environment effectively. Differences between the total L_{Aeq} measured by the DNMS and the SLM were between 0 and 1 dB(A) for all DNMS in all scenarios. These minor differences were expected as the SLM microphone could not be placed directly within the DNMS microphone array without interfering with DNMS results. Due to the size of the microphone arrays, DNMS microphones were also slightly closer to RNS than the SLM microphone at the centre of the array.

6.1 Unit A

In all-pass data, Unit A was able to effectively determine directions, within 5 degrees, and contributions, within 2 dB, of sources in the steady-state Scenarios 1 and 2. Both of the variable-state scenarios, Scenarios 3 and 4, reported significant contributions from AOI 2, which should not have occurred as that AOI contained no RNS. Further examination of raw data confirmed that Unit A was less accurate in determining the angles and contributions of the RNS in these two scenarios and that some “sliding” occurred where directions of contributions would drift during the variable-state scenarios. Scenario 3 had variance of 4 dB and Scenario 4 had variance of 2 dB.

In low-pass data, Unit A provided significantly different results for the same tests. Scenarios 1 and 2 had variance of 20 and 29 dB from expected results, respectively. Examination of raw data showed that Unit A lost track of the non-AOI RNS almost entirely in Scenario 1. Meanwhile, in Scenario 2, Unit A correctly determined the direction and contribution of the primary noise source but severely underestimated both the secondary and tertiary noise sources. Unit A performed moderately better in Scenarios 3 and 4, with variance of 6 and 4 dB respectively. However, Unit A correctly identified that AOI 2 did not contain a noise source, and allocated either zero or mathematically insignificant contributions to AOI 2 in all four scenarios.

The contrast between Unit A's handling of all-pass data compared to low-pass data is significant, as mining noise is typically measured off site at frequencies less than 1000 Hz. It should also be noted that the sum of the L_{Aeq} sources matched the measured overall L_{Aeq} within 0.7 dB in the all-pass results, but the difference between these totals was as much as 3.3 dB in the low-pass results. This indicates that up to 3 dB of low-pass noise was not being assigned to any direction.

6.2 Unit B

During the first test, Unit B was reasonably accurate at determining the directions of RNS although some “sliding” was observed in the non-AOI RNS during the variable-state scenarios. Scenarios 2 and 3 had variance of 6 and 4 dB, respectively. Scenario 4 had variance of 3 dB. It was noted in Scenarios 3 and 4, where results were expected to be equal, Unit B assigned the greatest contribution to the largest sector (non-AOI), the second greatest contribution to the second largest sector (AOI 2), and the lowest contribution to the smallest sector (AOI 1).

During the second test, Unit B did not reliably determine the directions of RNS. While there were only three RNS, Unit B assigned noise contributions in primarily five directions, effectively creating two phantom noise sources. It is unclear what caused this.

In the second test, Unit B exhibited somewhat similar results to the low-pass results from Unit A across all scenarios. Scenarios 1 and 2 had variance of 21 and 37 dB, respectively. Contributions from the RNS in AOI 2 were severely underestimated in both of these scenarios. Unit B also performed moderately better in Scenarios 3 and 4, with variance of 7 and 2 dB respectively. Examination of available directional data showed that some RNS in variable-state Scenarios 3 and 4 were only detected by Unit B when that RNS was dominant

6.3 Unit C

Unit C determined the directions and contributions of RNS in all four scenarios with a variance of 1 to 3 dB from expected results. It displayed the least variance in Scenarios 1, 3, and 4, where there were three primary noise sources producing equal acoustic energy. It displayed the most variance in Scenario 2, where the RNS produced primary, secondary, and tertiary noise levels at steady-state.

Two sets of AOI were calculated for Unit C to highlight the differences in contribution when the included angles of an AOI are increased or decreased. The first set of AOI, which had a larger AOI 2 and a smaller AOI 3, was compared to the second set, which had a smaller AOI 2 and a larger AOI 3. This had the effect of increasing the contribution from AOI 3 by up to 1.2 dB and decreasing the contribution from AOI 2 by up to 1.8 dB. An example of this is shown in Figure 7 for Scenario 1.

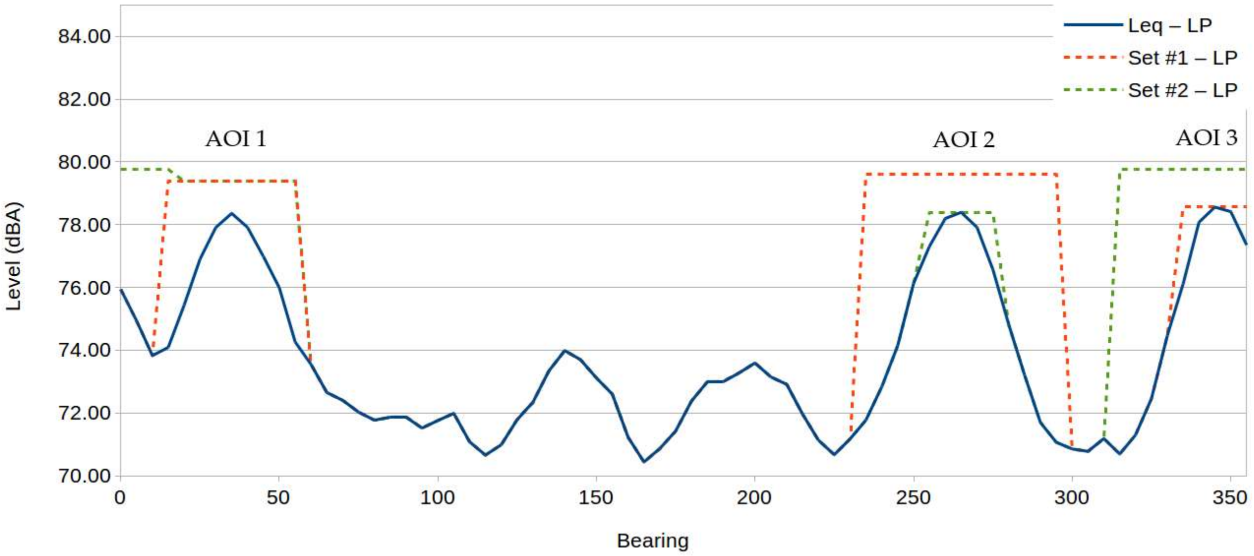

Figure 7 - Unit C Test - Scenario 1

Raw data from Unit C show that it detected a significant amount of background noise in the ambient environment that was not generated by RNS, as illustrated by Figure 7, for all scenarios. It should also be noted that the sum of the AOI was up to 1.7 dB less than the measured overall L_{Aeq}, implying that some RNS noise was not being assigned to the correct directions. By increasing the included angles of AOI, more of this background noise is included in calculating the contributions from the AOI. This contrasts raw data taken from both Unit B and Unit A, which show that secondary (and tertiary) noise sources are not always detected by the directional processor in some samples.

Another limitation of Unit C is that its directional processor only handles low-pass noise in the 125, 250, and 500 Hz octave-bands. This means that mining activity in the 63 Hz octave-band, such as exhaust noise from unattenuated haul trucks, may not be included by the directional processor in its estimations. Discussions with the manufacturer implied that the large microphone array may need to be doubled in size in order to accommodate the longer wavelengths of the 63 Hz octave-band.

7. CONCLUSION

All three DNMS that were tested measured the overall acoustic environment effectively to within approximately L_{eq} 1 dB(A) in all scenarios. These minor differences were expected as the SLM microphone could not be placed directly within the DNMS microphone array without interfering with DNMS results, and DNMS microphones were slightly closer to RNS due to microphone array sizes.

At higher frequencies, Unit A system was very effective at correctly determining the directions and contributions of steady-state noise sources, but somewhat less effective at correctly determining the direction and contributions of variable-state noise sources. At lower frequencies, Unit A system could only determine direction and contribution of the primary noise source in Scenario 2, and had difficulty when there were multiple primary sources, or, secondary and tertiary sources.

The directional processor of Unit B failed to generate directional data in three instances, despite the instrument continuing to measure omnidirectional noise levels. During the first test, Unit B was moderately effective at correctly determining the directions and contributions of variable-state noise sources. During the second test, two months later, Unit B only determined the direction and contribution of the primary noise source in Scenario 2, and had difficulty when there were multiple primary sources, or, secondary and tertiary sources.

Both Unit A and Unit B had difficulty processing low-pass noise from multiple directions simultaneously and performed best in Scenario 4 where there was generally one dominant noise source at any given time during the measurement, except at cross-over points where one RNS relinquished dominance to another RNS. It is unknown whether this could be attributed to the size of the microphone arrays relative to the larger wavelengths of low-pass noise, or to similarities of the source noise in terms of waveform maxima and frequency spectrum. More research, including testing at discrete frequencies, would be required to determine if this is the case.

Unit C determined the directions and contributions of noise sources in all four scenarios with a maximum variance of 3 dB from expected results. It was very effective at correctly determining the directions and contributions of multiple steady-state primary noise sources, and slightly less effective at determining the contributions of secondary/tertiary sources and variable-state sources. However, it was noted that the size of AOI had an effect on measured contributions and that the directional processor does not calculate contributions in the 63 Hz or below octave-bands.

Unit B and Unit C only provided low-pass directional data at the time of testing, and the directional performance of these instruments was not evaluated for higher frequencies. For near-field assessment of broad spectrum noise, such as measurement of nearby power stations or rail yards, results indicate that Unit A could be an effective management tool (with consideration of all four scenarios). For far-field assessment of low-pass noise, such as measurement of mining operations at a distance, results indicate Unit C could be an effective management tool. However, none of the DNMS are considered sufficiently accurate to be suitable for compliance purposes.

This was not a laboratory-controlled test and only one unit of each DNMS variety was tested. While all care was taken to test units that appeared to be operating normally, more research would be required to draw stronger conclusions regarding the capabilities and limitations of these systems.

REFERENCES

Bullen, R 2001, ‘A system for automatically detecting the direction and level of noise sources, *Proceedings of Australian Acoustical Society Conference*, Australian Acoustical Society, Canberra, p.4.

Bullen, R & Lawrence, B 2007, ‘Measured performance of a directional noise monitoring system’, *Proceedings of 14th International Congress on Sound & Vibration*, International Institute of Acoustics and Vibration, Cairns, Queensland. p.3.