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Managing the Uncertainty of Long-distance Sound Propagation from a Large Industrial Noise Source

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ABSTRACT

The attenuation of a sound signal over long distances is accounted for by atmospheric absorption, atmospheric stability, ground effects, barriers and spherical spreading. Conversely, the propagation of sound over long distances can be enhanced by source to receiver gradient winds and vertical temperature profiles that create downward refraction of the sound waves. While the nature of each of these phenomena is well understood, the prediction of the sound propagation over long distances from a large industrial source such as an open-cut mine is inconsistent with the measured sound pressure level attributed to the source. The uncertainty around the theoretical model predictions and the measured source sound pressure levels in a multi-source environment creates a control problem when managing day to day mining operations. This paper investigates the relationship between the measured and predicted sound pressure levels at three continuous noise monitors along a propagation path at distances of 500m, 1500m and 2500m from the source. The objective of the analysis was to reduce the uncertainty in the measurement of the source's contribution at the noise monitor located in a multi-source environment 2500m from source.

Keywords: Sound Emissions, Control, Industrial, Continuous Monitor

1. INTRODUCTION

Environmental noise is defined as unwanted or harmful outdoor sound created by human activities (1). Major sources of noise include road and rail traffic, aircraft, industrial activity and power generation. The challenge with measuring, assessing and reporting environmental noise has been the subject of numerous research articles over many years. In recent years the deployment of permanent monitoring networks (2,3,4,5) has resulted in the development of techniques for the dynamic interpolation (tuning) of noise maps using continuous noise monitoring data (3,5,6), the development of pattern classification algorithms to separate target and interfering noise sources recorded by continuous noise monitors (7), the assessment of uncertainty in monitoring data (8,9,10) and the development of innovative methods for communicating and presenting the monitoring data in real time (11,12,13).

For many mining operations in New South Wales (NSW) Australia, the management of noise impacts is a key consideration during the design, planning and operational phases of the mining operation. During the design and planning phases computer noise models are used to predict the sound pressure level generated by an industrial operation at a specific receiver location for comparison against relevant noise standards. If the predicted sound pressure level exceeds the relevant noise immission standard for the receiver type, there is an expectation that control strategies would be implemented to reduce the immission level. As an interactive/iterative tool noise models can be used to assess the effectiveness of different noise control strategies that could be implemented by an industrial operation. The desired outcome is that the industrial operation achieves the relevant noise standards at all receiver locations under all temporal variations.

During the operational phase a mine will be subject to a range of noise related operation constraints including self-imposed conditions to meet corporate or community expectations and conditions imposed by a range of different regulatory authorities (14). Noise criteria or noise limits imposed by

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regulatory authorities are typically single numerical values that vary according to the spatial differences between receiver locations and the temporal differences between the day (0700 to 1800), evening (1800 to 2200) and night (2200 to 0700). There is a cost associated with the implementation of control strategies and there is also a cost associated with the failure to successfully implement appropriate noise control strategies or with the implementation of unwarranted controls.

In the NSW Coal Industry, compliance with noise criteria is assessed through monthly attended noise monitoring. The attended noise monitoring is undertaken at defined locations, at regular intervals as set out in development approvals and environmental licences[2], to quantify and describe the acoustic environment at each monitoring site. The results of the attended noise monitoring are recorded, analysed and compared with approved noise criteria to assess compliance (4,15).

In addition to compliance monitoring most of the open-cut coal mines in the NSW coal fields of Australia have noise performance management systems in place to assist in maintaining compliance with noise criteria at sensitive receiver locations in the surrounding rural communities. Noise performance management is undertaken using a combination of continuous real-time noise monitoring supplemented with attended monitoring using mine personnel or an independent acoustic consultant. A noise performance management system provides a mine with real-time noise levels and local meteorological data at each of the continuous real-time noise monitoring locations, and triggers alarms when predefined noise levels have been reached. An alarm from a continuous noise monitor will initiate a noise management action to change aspects of the mining operations in order to reduce noise immission levels at the monitoring location (4,15,14).

Over the last 18 years the mining industry in NSW Australia has installed over 60 continuous noise monitors either individually or as part of a continuous noise monitoring network. The installation of continuous noise monitoring networks has facilitated the move away from an operational framework based around after-the-fact monitoring (16) to one that enables the strategic management of the noise source(s). However, to adequately facilitate this, these systems need to collate, analyse and report on the real-time noise monitoring data, and the accompanying meteorological conditions and operational parameters associated with the noise source(s).

The effectiveness of the mine's noise management system and the changes implemented to control noise impacts relies on the correct interpretation of the monitoring data when reporting the source-of-interest's contribution to the acoustic environment.

2. The Source-of-Interest

In this paper, the noise source-of-interest is an open-cut coal mine located in the Hunter Valley coalfields of NSW Australia. The mine has installed a continuous noise monitoring network in accordance with development consent requirements regulated by the NSW Government's Department of Planning and Environment. The development consent requires the evaluation of the mine's noise immission against noise impact assessment criteria specified in the development consent using a combination of continuous noise monitoring and supplementary attended noise monitoring.

The mine's continuous noise monitoring network consisting of five noise monitors, three weather stations with 10-metre towers and five supplementary weather stations co-located with the noise monitors. The noise monitors measure and report on the acoustic environment at each monitoring location. The primary reporting metrics include: LAeq,15minute; LA90,15minute; and Leq,15minute at 1/3 octave intervals. The weather stations measure and report wind speed and wind direction, ambient temperature, humidity and rainfall at 10-minute and fifteen-minute intervals.

One of the noise monitors (identified here as NM3 in Figure 1) is located in the midst of a small rural community to the south-east of the mine. Two of the noise monitors, NM1 and NM2, are located between NM3 and the mine. NM1 is located on the southern highwall overlooking the open-cut pit and NM2 is located approximately 500m to the south-east of the active mining area in an elevated location. The two other noise monitors are located to the east of the mine.

The location of the source/mine-of-interest, noise monitors NM1, NM2 and NM3 and cross section profile from the active mining area to the monitoring locations are shown in Figure 1.

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[2] A formal notice of approval issued by a regulatory authority for the implementation of a specific development proposal described in a development application. A development consent typically includes a detailed list of conditions under which the development can be operated.

Figure 1 – Location of mine-of-interest in the background in relation to continuous noise monitors NM1, NM2 and NM3, weather stations Met1 and Met2, arterial highway, arterial railway, local roads and adjoining mining operations.
above: (c) Google Earth, CNES / Airbus

The noise immission limit at NM3 for noise emitted by the source-of-interest is 40 dB(A) LAeq,15minute and applies for the day, evening and night periods. The noise immission limit at NM3 is applicable for wind speeds up to 3m/s (measured at 10m above ground level) for stability categories A to E[3] and wind speeds up to 2m/s for stability category F.

The continuous noise monitoring unit at NM3 is not used to assess compliance but is used as an operational management tool. The data from the noise monitoring and associated weather stations is presented on a web page and the unit has SMS alarm capabilities. The primary function of the noise monitor at NM3 is to report the LAeq,15-minute sound pressure level attributable to the source-of-interest, the mine located 2500m the north-west of the monitoring location. The SMS alarm function is used by the Mining Supervisors to instigate noise-based management actions in the active mining areas.

In 2017 the SMS alarm system at NM3 was augmented with a SMART technology visualisation tool updated at 5-minute intervals. With this tool in place the period of time the 15-minute LAeq noise level attributed to the source-of-interest exceeded the 40 dB(A) criterion at NM3 was reduced 60%, from 290 hours in the winter evening/night period of 2017 to 110 hours in the winter evening/night period of 2017.

3. Trends and Patterns

Shneiderman (18) notes that the exploration of data becomes increasingly difficult as the volume of the data increases and that data abstraction through visualisation can reveal patterns, clusters, gaps and outliers in the data.

[3] Pasquill-Gifford-Turner stability categories (17)

During 2017 the 15-minute monitoring data from NM3 was integrated with monitoring data from the continuous noise monitor NM2 and weather stations Met1 and Met2. The data was compiled daily to identify trends and patterns that could be used to improve the interpretation of the data from individual units and as a network. The analysis targeted trends and patterns that linked the SMS alarming function to the total LAeq acoustic environment at NM3, the estimated source-of-interest contribution at NM3 and NM2 (NM3 SoI1 and NM2 SoI1), the calculated lapse rate to identify the presence of inversion conditions, and wind speed and direction at 15-minute intervals.

The prototype of the SMART technology visualisation tool was developed in 2017 based on the observations drawn from the collation of the 15-minute monitoring data. The benefits realised in 2017, i.e. a 180-hour reduction in the source-of-interest exceeding 40 dB(A) at NM3, was due to a combination of the quantification of the trends and patterns into algorithms used by the visualisation tool and the augmentation of the 15-minute SMS alarm system with the 5-minute updates to the visualisation tool.

Notwithstanding the improvements gained in 2017, in 2018 the 15-minute LAeq noise level attributed to the source-of-interest was reported to exceed the 40 dB(A) criterion at NM3 for 130 hours of the winter evening/night period. To achieve further improvement in control of the noise immissions at NM3, the uncertainty in the quantification of the source-of-interest contribution to the acoustic environment at NM3 needed to be addressed.

4. Data Collation

4.1 Pattern Identification

The initial improvements in the noise control of the source-of-interest were attributed to the increase in the temporal resolution of the data to 5-minute intervals and the increased visibility of relevant data. To gain further improvement in the noise control the relationship between the data collected by the paired monitors NM2 and NM3 was investigated. The data from monitor NM1, located on the southern highwall of the open-cut pit, was not used as it was adversely affected by individual machine activities and was not representative of the mine as a continuous single source.

The continuous monitoring systems collect a range of metrics in addition to the LAeq,15minute data. This includes 1/3 octave levels as 10-second, 5-minute and 15-minute Leq, Ln percentiles and the amplitude, frequency and angle of the dominant noise source at 6-second intervals. The objective was to use this data to reduce the uncertainty in the quantification of the source-of-interest contribution to the acoustic environment at NM3. To achieve this, the analysis of the high-resolution data considered two aspects: 1. finding a narrow set of items in the large dataset that satisfied specific conditions; and 2. understanding unexpected patterns identified in the large dataset (18).

4.2 Source Contribution at NM2

Figure 2 shows a 2-hour run chart of 10-second all pass LAeq data and all pass LCeq data recorded at NM2 between 02:00 and 04:00. The measured LAeq of the acoustic environment over the 2-hour period in Figure 2(a) is 50.0 dB(A)[4]. The standard deviation of the arithmetic average is 4.4 dB.

The acoustic environment represented by Figure 2 includes the source-of-interest and coal trains passing along the rail corridor located between the source-of-interest and the monitoring location. The high energy events shown in Figure 2 are the train pass-by events. The 10-second LAeq data can be compiled into two statistical distributions to represent the noise sources: a normal distribution for the mine noise and a gamma distribution for the train pass-by noise.

In Figure 2(a) the divide between the two noise sources has been set at 51 dB(A) using the 85th percentile of the measured data. By separating the two noise sources, the measured LAeq of the mine noise over the 2-hour period is reported as 45.3 dB(A) and the measured LAeq of the train pass-by is 56.5 dB(A). The standard deviation of the arithmetic average mine noise is 2.1 dB. The measured LCeq of the mine noise over the 2-hour period is 58.3 dB(C) and the measured LCeq of the train pass-by is 67.2 dB(C). The standard deviation of the C-weight arithmetic average mine noise is 1.6 dB.

The application of a low-pass filter on the 10-second 1/3 octave data was also investigated. The difference between the measured LAeq of the mine noise in Figure 2(a) and the equivalent low-pass (25 to 630 Hz inclusive) sound pressure levels is 1.4 dB. Applying a low-pass filter reduces the arithmetic average standard deviation to 2.0 dB.

[4] One decimal point is used to demonstrate the math, not the accuracy of the method described.

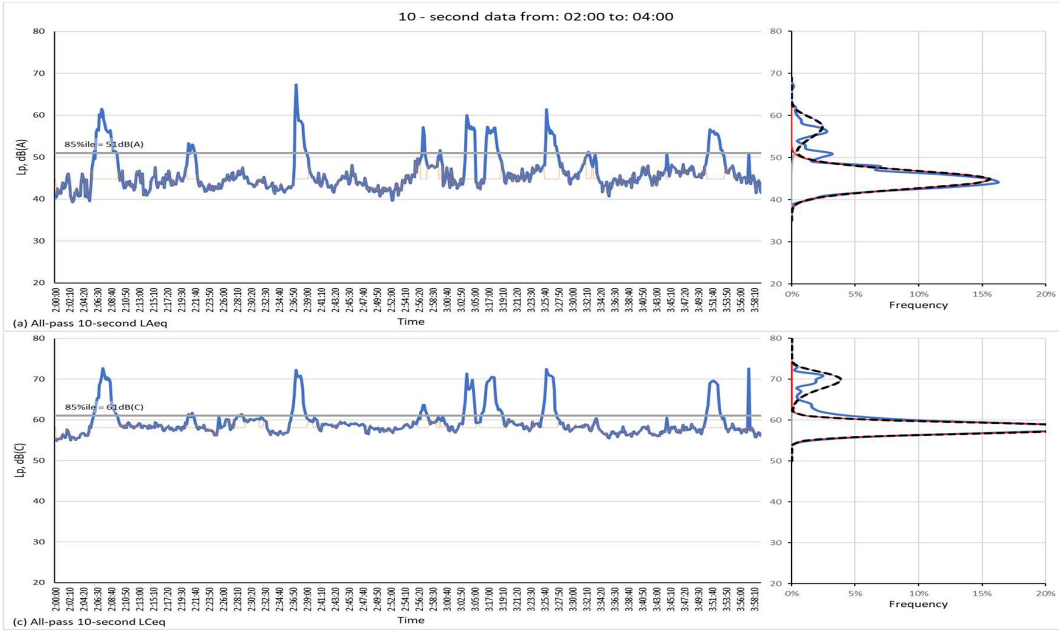

Figure 2 – Pattern analysis in 10-second data collected by NM2

This method has been used to establish a reference sound pressure level of the source-of-interest at the reference monitoring location NM2 by removing the contribution from the train by-pass events. This method can also be used to filter out contributions to the acoustic environment from car drive-by events on local roads and overhead plane and helicopter fly-over events.

4.3 Source Contribution to NM3

The comparative 2-hour all pass LAeq and LCeq run charts for NM3 are shown in Figure 3.

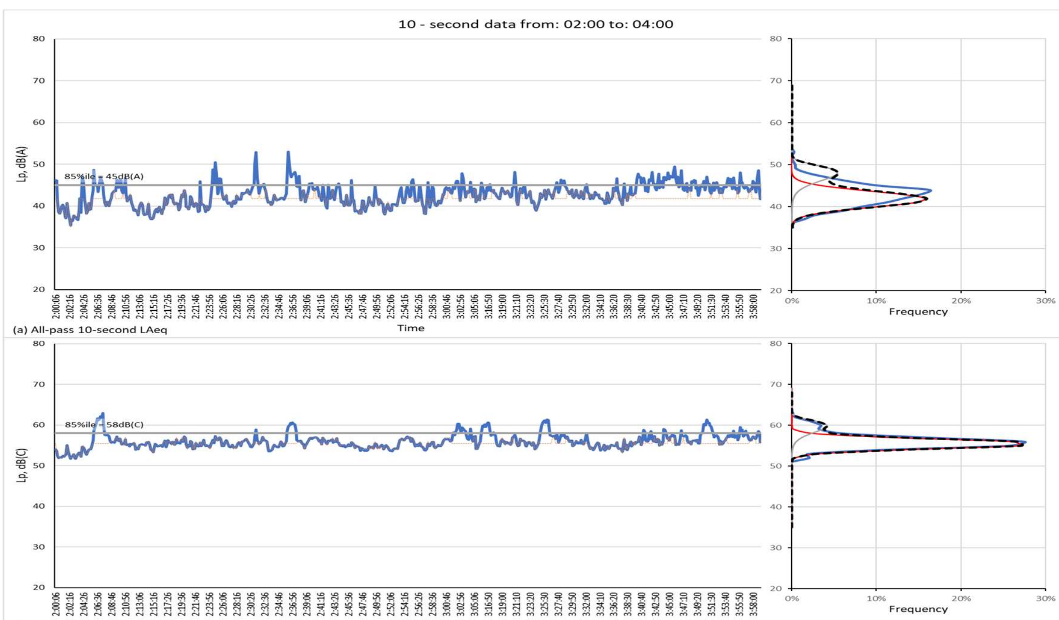

Figure 3 – Pattern analysis in 10 second data collected by NM3

The source-of-interest at NM3 is heavily masked by road traffic noise from an arterial highway 900m to the south of the monitoring location. Other noise sources contributing to the acoustic environment at the monitoring location include an open-cut coal mine to the south-east, surface facilities for an underground mine to the west and open-cut mines to the west.

The measured LAeq of the acoustic environment over the 2-hour period in Figure 3(a) is 44.0 dB(A). The standard deviation of the arithmetic average is 2.4 dB. While the influence of the train pass-by events shown in Figure 3(a) is indistinct in the A-weighted run chart each event is distinguishable in the C-weighted run chart in Figure 3(b).

Comparison of the C-weighted run charts in Figure 2(b) and Figure 3(b) suggests it could be possible to establish a quantitative relationship between the sound pressure level of the train by-pass events at NM2 and NM3. However, the audio recordings from 02:30 to 02:45 from NM2 and NM3 (Figure 4) show that the temporal alignment of the signal from the train pass-by event is affected by the spatial differences between monitoring locations and the railway corridor. As a result, a quantitative relationship for train pass-by events could not be developed for the two monitoring locations. The alternative was to either remove the train pass-by data from the 10-second data sets of both monitoring units or, to facilitate further analysis, substitute the arithmetic mean of the residual data for the train pass-by events. The latter option was adopted.

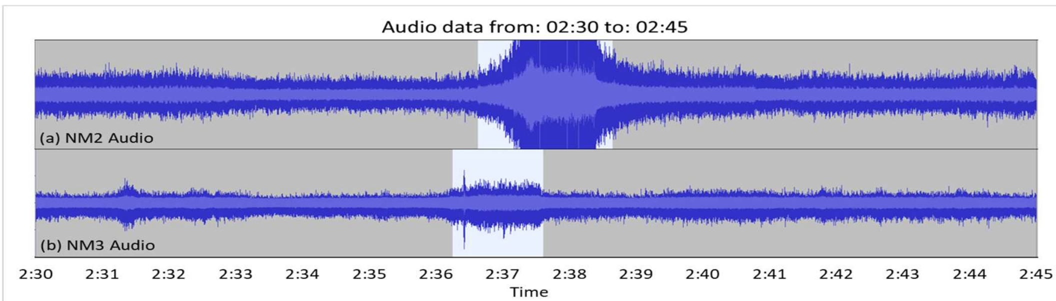

Figure 4 – Analysis of audio recordings showing offset in temporal alignment of the signal from the train pass-by event

4.4 Predictive Noise Modelling

A predictive noise model was used to model the mining operations under a 1.7 to 2.1 m/s wind from 315 degrees under atmospheric stability conditions ranging from class D to class F (lapse rate of 5 deg/100m). The predicted A-weighted 1/3 octave spectrums for the modelled conditions for NM2 and NM3 are presented in Figure 5.

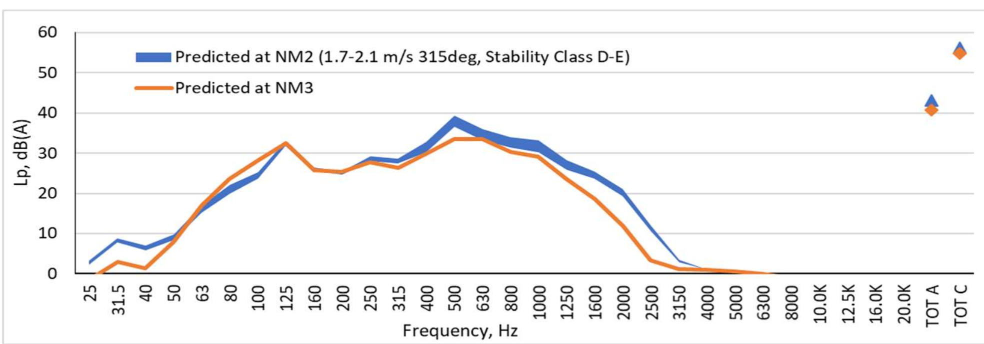

Figure 5 – Comparison of predicted sound pressure level of the soure-of-interest at NM2 and NM3 under 1.7 to 2.1 m/s wind from 330 to 335 degrees and class D to F stability conditions

The prevailing meteorological conditions between 02:00 and 04:00 enhanced the propagation of the sound signal from the source-of interest towards NM2 and NM3. The differences in the predicted and measured A-weighted and C-weighted sound pressure levels identified in Sections 4.2 and 4.3 above are tabulated in Table 1.

Table 1 – Comparison of Predicted and Measured Sound Pressure Levels

Monitor Location	Predicted, Leq		Measured, Leq	
	dB(A)	dB(C)	dB(A)	dB(C)
NM2	44.3	56.9	45.3	58.2
NM3	40.8	54.8	42.1	55.6

Comparison of the predicted total A-weighted and C weighted sound pressure levels at NM2 with the measured source-of-interest sound pressure levels at NM3 indicate the noise model is under predicting by approximately 1 dB. However, this would not affect the predicted differential between NM2 and NM3 of 3.5 dB.

5. Analysis

To reduce the uncertainty of when and how much noise control should be implemented to reduce the noise immission levels at the receiver location all the elements described above are required to establish the relationship between the paired monitors NM2 and NM3. A natural response would be to use the reference signal at NM2 and predict the likely sound pressure level at NM3. However, this does not account for the deep fading events described by Wilson (19) and could result in an over-prediction of the noise immission levels.

The method that is proposed is the validation of the noise immission levels at NM3 when the source-of-interest level reported by NM3 is within 2 dB of the noise criterion. If, for example, the reported source-of-interest level at NM3 is reported at 41.0 dB(A), the noise immission level at NM2 would need to be at least 44.5 dB(A).

Figure 6 applies the predicted distance attenuation relationship between NM2 and NM3 to the reported 5-minute LAeq source-of-interest sound pressure levels at NM3 and compares these results with the measured sound pressure levels at NM2. The source-of-interest sound pressure level at NM3 is the noise immission level the Mining Supervisors compare against the criterion at NM3 and is the metric used to initiate system alarms.

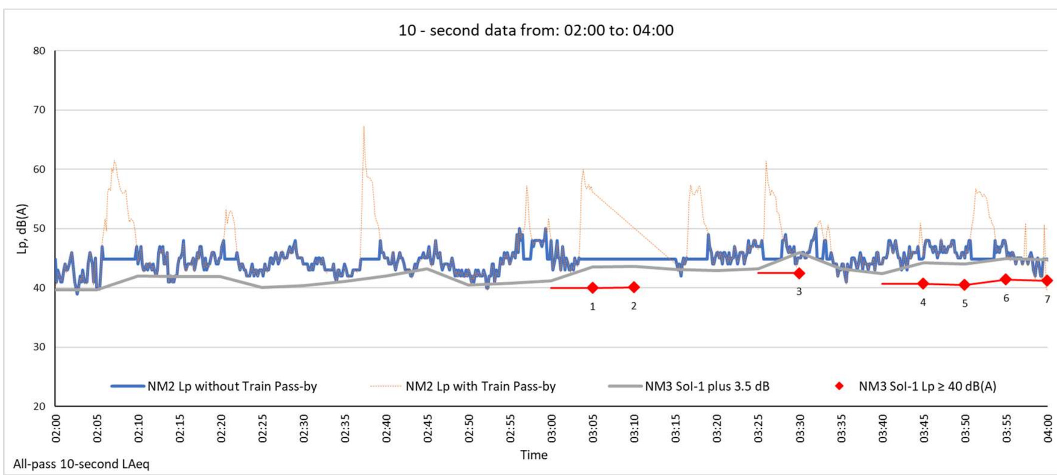

Figure 6 – Comparison of reported source-of-interest sound pressure level plus 3.5 dB with the measured sound pressure level at NM2. The chart also shows the potential alarm points at NM3 when the source-of-interest sound pressure level is reported ≥40 dB(A).

The results in Figure 6 indicate alarm points 3 to 6 are all valid as there is sufficient sound energy at NM2 to support the propagation of the sound signal from the source-of-interest to NM3. Alarm points 1 and 2 are potentially ambiguous as a train pass-by event masked the sound signal from the mine, the source-of-interest. Alarm point 7 may be over predicted as the sound energy at NM2 is less than the energy required to support the reported 41.0 dB(A) for the source-of-interest at NM3.

6. Conclusion

The method proposed in this paper to reduce the uncertainty in the identification of source contribution over long distances, relies on the use of paired noise monitors with one unit as a reference monitor. With a paired noise monitor installation, the reference monitor is used to validate a predictive noise model of the source-of-interest and provides a reference signal against which the second monitor, located at the receiver location, can be compared. The analysis shows that this method reduces the uncertainty of source contribution at the receiver location.

It was found from the analysis of the three continuous noise monitors that the noise monitor used as a reference point for the source-of-interest must be located where the source-of-interest presents as a high energy single source continuum.

The methods described in this paper also demonstrate that source uncertainty due to extraneous events, such as a train pass-by, that mask the high energy noise continuum of the source-of-interest at the reference monitor, can be reduced by analysing the 10-second 1/3 octave data.

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