The Harmonoise noise prediction algorithm: Validation and use under Australian conditions

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ABSTRACT

The most commonly-used algorithms for external noise level prediction in Australia are the ISO 9613 and CONCAWE algorithms, neither of which allows detailed investigation of propagation under adverse meteorological conditions. The ENM algorithm has been accepted and used for this purpose, but it is not open-source and the only software that implements it is now out of date and not supported. The European Harmonoise algorithm has been developed over more than 10 years, and offers a consistent method for prediction of noise levels under arbitrary meteorological conditions. It is implemented in open-source code, and has been validated to some extent in Europe. This paper provides a detailed comparison between Harmonoise and ENM predictions, as well as a comparison with measurement data recorded in Australia. Recommendations are made regarding the usage of the algorithm under Australian conditions. The software available from the Harmonoise project allows basic point-to-point calculations, and can be incorporated into more sophisticated modelling procedures.

INTRODUCTION

Robust assessment of noise from large industrial operations requires the prediction of noise levels from multiple sources at distances up to several kilometres, under the range of meteorological conditions prevailing at the site. This is well known to be a very challenging task (see for example NPL 2011). At these distances, noise levels depend strongly on the type and profile of the intervening ground, and particularly on meteorological conditions. Levels from a fixed source can vary dramatically on time scales ranging from seconds to hours, in ways that cannot be explained in terms of bulk meteorological properties such as wind speed and linearised temperature gradient. Without extremely detailed meteorological data, the goal of predicting noise levels at a specific time under specific conditions, to within a few dB, appears out of reach (Wilson & Pettit, 2009).

Nevertheless, it may still be possible to predict *statistical* properties of the distribution of actual noise levels, such as energy-mean values or higher percentiles of the noise level, based on *statistical* properties of the bulk meteorological data. This provides sufficient information to assess the potential noise impact of a proposed development.

In Australia, for predicting noise at large distances from non-transport sources (such as mining operations), the most commonly-used algorithms are:

- ISO 9613-2 1966 "Acoustics – Attenuation of sound during propagation outdoors – Part 2: General Method of Calculation";
- CONCAWE report 4/81 (Manning, 1981); and
- ENM (Tonin, 1984).

Of these, the first two are similar, in that they allow only basic corrections for different meteorological conditions (although CONCAWE corrections are somewhat more detailed than those in ISO 9613), and in particular they do not allow for any interaction between meteorology and shielding, which is known to be important in determining the likely increase in noise levels under adverse conditions. These algorithms are implemented in standard prediction programs such as SoundPlan and CadnaA.

The ENM algorithms are described in general terms in Tonin (1984), and are implemented in specific software, but precise details of the implementation are not available. A number of practitioners have found that they provide a more robust prediction method than the other alternatives, and in particular allow for an interaction between meteorological conditions and shielding.

Techniques have been developed, using the ENM algorithms, to calculate noise levels from a large number of sources under the range of bulk meteorological conditions applying at a site, and from these to estimate the statistical distribution of noise levels at a receiver. Experience indicates that this allows important parameters, such as the noise level exceeded for 10% of the time, to be estimated with reasonable accuracy.

However, the specific software that implements the ENM algorithms is very old, and appears to be unusable under modern operating systems including Windows 7. The author understands that there are no plans to update this software.

Another set of algorithms, known as Harmonoise, has been developed in Europe over a period of about ten years (Van Maerke 2006). The work forms part of a larger project conducted jointly by nine European countries, intended to "harmonise" their noise prediction methodologies.

These algorithms incorporate sophisticated modelling of terrain and meteorology, as well as features such as scattering from turbulence. The Harmonoise algorithms are gaining acceptance in Europe for applications such as noise mapping. Significantly, the canonical Harmonoise point-to-point calculation procedure is available as open-source C++ code and so can be implemented by any suitable enclosing program.

This paper examines the Harmonoise algorithms with a view to their use in predicting noise from industrial sources in Australia. The predictions are compared with those from ENM, and with results from a series of measurements conducted in the Collie Basin, WA in 2007. Finally, recommendations are provided concerning the use of these algorithms for predicting noise levels under typical conditions found in Australia.

THE HARMONOISE ALGORITHMS

Details of the Harmonoise algorithms are provided elsewhere (Salomons et al, 2011) and this paper provides only a summary of the relevant points.

Note that although the Harmonoise project includes additional methodologies for predicting noise from specific sources such as road and rail traffic, this paper considers only the basic "point-to-point" algorithms which predict the attenuation between a single source point and a single receiver, with a known ground cross-section between them. Issues such as the optimal generation of cross-sections and the best way to model specific sources would be incorporated in an enclosing program, and would be common to all algorithms.

Harmonoise calculates "excess" attenuation in 1/3-octave frequency bands by considering the combined effects of air absorption, the ground effect, shielding by topography (which may include barriers or buildings), atmospheric refraction and atmospheric scattering. The effect of attenuation by spherical spreading must be added to these results.

Air Absorption

Attenuation by air absorption is modelled as in ISO 9613 using tables of absorption per metre by frequency, temperature and relative humidity.

Ground Effect and Shielding

The algorithm proceeds by the following process.

1. Identify the most important shielding point between the start and end of the segment (above line-of-sight).

2. If there is no such point, calculate attenuation through a combination of the ground effect and any shielding that may exist below the line-of-sight.

3. If there is a shielding point above line-of-sight, calculate shielding from this point. Then consider the segments before and after the shielding point and iterate recursively from point 1, summing attenuations from each segment, until there is no shielding above line-of-sight.

Attenuation from shielding is calculated using a formula by Deygout (1966) that is close to the traditional Maekawa formula used in other algorithms. Ground effects are calculated using a variation of the well-known ground attenuation formula (see e.g. Rossing 2007) which depends on the complex ground impedance. Using the model of Delaney and Bazley (1970) this can be represented by a flow resistivity. Harmonoise also allows for input of a spread of heights for both source and receiver, which results in a "smoother" spectrum of attenuation values rather than the peaks and troughs at specific frequencies that occurs with precisely-defined heights.

In general, the ways in which ground effects and shielding are handled in Harmonoise are comparable to those in ENM, but somewhat more complex and mathematically rigorous.

One issue is the way in which below-line-of-sight barriers are handled, and in particular the transition between attenuation due to a below-line-of-sight barrier and simple ground effect. The Hamonoise code ensures that attenuation due to the assumed barrier is generally preferred, even in cases where this would not generally be expected (such as the "valley" scenarios described below). Ground effect is assumed only where the ground is relatively flat AND a significant distance below the line of sight. In the calculations below, the Harmonoise code was modified slightly to prefer ground-effect attenuation whenever the ground is relatively flat OR a significant distance below line of sight. However, as described below, there appear to be other issues with the ground effect calculation, especially when coupled with scattering.

Refraction

Refraction effects due to meteorology are handled in Harmonoise by allowing the ground to bend up or down with a radius of curvature determined by the vertical sound speed gradient in the atmosphere. There is no specific "correction" for refraction. Rather, where the sound speed gradient is positive, and sound is therefore refracted down, the ground is "warped" downward using a conformal transformation of the coordinates, so that ground effect and shielding are both reduced. For a negative sound speed gradient the reverse occurs. In principle this is physically realistic, and certainly preferable to the addition of "corrections" after the effects of ground effect and shielding have been calculated in the absence of refraction. The procedure used in ENM can be considered a hybrid of these two approaches.

The vertical sound speed profile in the atmosphere is considered in Harmonoise to be the sum of linear and logarithmic components:

$$c_{eff} = c_0 + Az + B\ln(1 + z/z_0) \quad (1)$$

where c_{eff} is the effective sound speed at height z, c_0 is the speed at ground level, z_0 is the "roughness length" of the ground, generally taken to be about 0.1m, and A and B are co-efficients to be determined.

The gradient of c_{eff}, which is directly related to the inverse of the radius of curvature for "ground-bending", is

$$dc_{eff}/dz = A + B/(z + z_0) \quad (2)$$

To provide a single radius of curvature, (2) must be evaluated at a specific height. The height chosen is, for downward refraction, the maximum height of a ray that would travel directly from the source to the receiver, and for upward refraction, the mean of the source and receiver heights. The latter choice leads to relatively small radii of curvature for upwind propagation, which may turn give excessive attenuations in some circumstances. This possibility could not be investigated in detail due to other associated issues as described below.

Given sufficient data, or a sufficiently detailed model, c_{eff} can be calculated at a number of heights, values of A and B can be estimated from a linear / logarithmic regression, and these values can be input directly into the Harmonoise point-to-point calculation. Data from a TAPM air quality model could be used for this purpose.

Where only general meteorological properties are available, the situation is more difficult. The Harmonoise literature (Defrance et al) discusses estimation of A and B based on the Monin-Obukhov similarity theory of atmospheric stability. This postulates a set of dimensionless parameters known as friction velocity, temperature scale and Monin-Obukhov length, which can be estimated from wind speed, cloud cover and day/night, and which in turn can be related to A and B through the theory.

Unfortunately Monin-Obukhov theory breaks down in the case which is generally most important for sound propagation – a stable night-time atmosphere with very low wind. Hence the Harmonoise program incorporates tables that provide estimates of the dimensionless parameters under various conditions, but which do not necessarily accord with the underlying theory. The tables appear to have been constructed so that the parameter values give values of A and B that are in accord with profile measurements. However these measurements were made in Europe, and there is no guarantee that the same tables will give reliable results in Australia.

A more straightforward way to estimate co-efficients is as follows. There are a number of standard ways to estimate a temperature inversion strength in degrees C per 100m - these are commonly used in Australia with the ENM program and many practitioners are used to estimating inversion strength in this way. The inversion strength can be taken as defining A in (2), since to first order

$$dc_{eff}/dz = (1/2)(\kappa R/c_0)dT/dz \qquad (3)$$

(for zero wind speed) where κ is the ratio of specific heats for air (~1.4) and R is the specific gas constant for dry air (~287 J/kg/K). Hence if S is the inversion strength in degrees per 100m,

$$A \sim S/170.9 \qquad (4)$$

Wind speed can be considered to vary logarithmically with height, to a first approximation. Then from (1), if W is the vector wind speed from source to receiver, measured at 10m,

$$B \sim W/4.62 \qquad (5)$$

This provides a direct method of specifying meteorological parameters in a form that is more familiar to Australian practitioners.

Turbulent Scattering

Scattering by atmospheric turbulence effectively sets a limit to the attenuation achievable through shielding, the ground effect and negative sound speed gradients. In ENM this is implemented by simply limiting the potential attenuation values produced by the program.

In Harmonoise there are two separate "turbulence" effects.

- A loss of coherence between direct and reflected sound, due to the sound paths travelling by different routes, limits the ground effect. As noted below, there appear to be issues regarding the application of this effect.
- The barrier effect is limited by scattering of sound into areas that would otherwise be shielded. In Harmonoise this also limits the reduction under negative sound speed gradients, since in this case the reduction is largely due to shielding by the "bent" ground.

These are both controlled by the same "turbulence strength" parameter C and the effects increase at higher frequencies and greater distances. At 1KHz and 1000m, the effective limitation on barrier attenuation is 35 + 10log(C). The Harmonoise literature suggests a typical value for C would be 5 x 10^{-6}. However in calculations reported below a value of 10^{-5} was used as this appeared to give better correlation with both ENM and measured results.

COMPARISON WITH ENM

Calculations were performed in both ENM and Harmonoise for a number of typical ground profiles, as shown in Figure 1, and a number of meteorological conditions, as shown in Table 1. In all cases the ground was modelled as acoustically soft (flow resistivity 200,000 MKS rayls/m). Attenuations were calculated in 1/3-octave bands, and results were summarised by calculating the A-weighted SPL of a typical source as predicted at the receiver point.

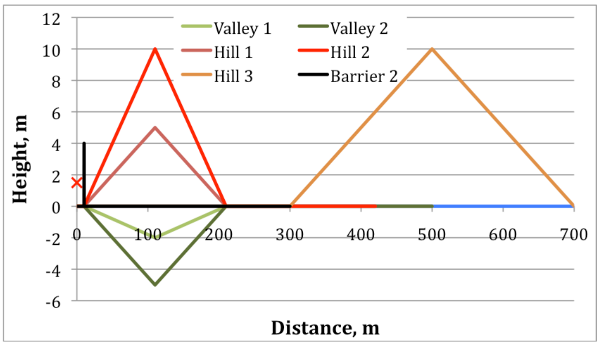

Figure 1 Ground profiles for comparison ("Barrier 1" is as for "Barrier 2" but 2m high). Source location is shown as "x". Receivers are at various distances as indicated in results.

Table 1 Meteorological conditions for comparison

Description	Conditions
Upwind	3m/sec upwind, -1.8°/100m temp. grad.
Neutral	No wind or temp. grad.
Downwind	3m/sec downwind, no temp. grad.
Inversion 1	No wind, 3°/100m temp. grad.
Inversion 2	1m/sec downwind, 3°/100m temp. grad.

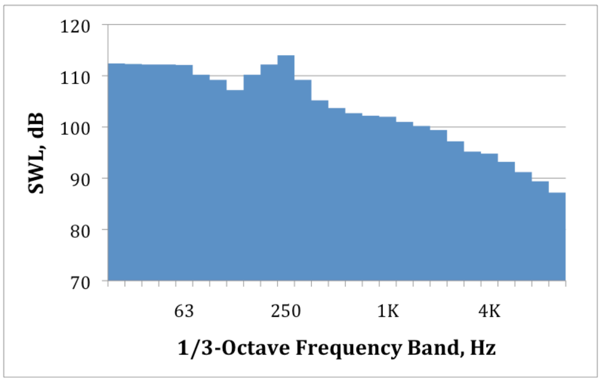

Figure 2 "Dozer" spectrum used as a typical source

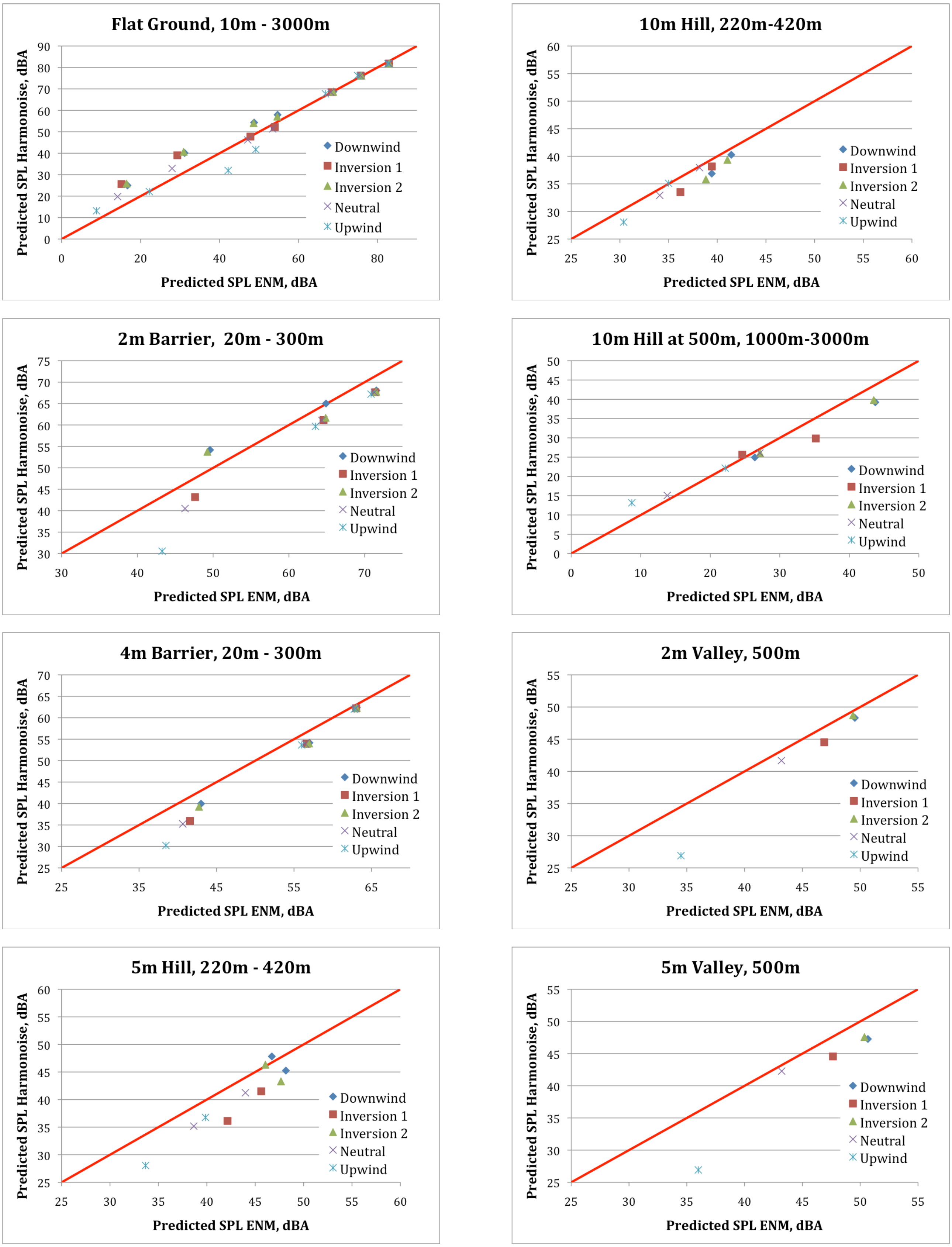

Figure 3 A-weighted noise levels from a typical source predicted from ENM and Harmonoise

The spectrum used is shown in Figure 2 and is typical of a dozer or similar plant. Trials using alternative spectra gave very similar results.

Calculated A-weighted noise levels are compared in Figure 3 for each topographical situation and meteorological condition. A number of points are clear from these figures.

1. In general the agreement between the two prediction methods is reasonable. The average difference between the predictions over all conditions is 1.1 dB, ENM being higher. However, the rms difference is 4.2 dB, and in a few cases the difference is up to 10dB.

2. Over flat ground at large distances, Harmonoise tends to predict higher than ENM – in some cases significantly higher. However, this scenario rarely arises in practice as it assumes perfectly flat ground over distances of at least several hundred metres. The difference appears to be due to the scattering assumed in Harmonoise, and can be "tuned" to some extent by changing the assumed "turbulence strength".

3. In most other cases, Harmonoise tends to predict lower than ENM by 1-2 dB. However, for upwind propagation, particularly at large distances, the difference can be up to 10dB. Investigation revealed that this is due to the way in which Harmonoise treats barriers and ground effect when propagation is close to the ground. These cases often arise in upwind propagation because the ground is "bent" upward toward the line of sight. When a barrier is found (either above or below line-of-sight), the ground effect is calculated for the segments before and after the barrier, but the source and/or receiver height in this calculation is zero. This results in high predicted attenuations, particularly if turbulence is included, because a zero source or receiver height negates the coherence-loss effect of turbulence. This effect also shows up in comparisons with recorded data shown below, and appears to be an anomaly in the current algorithm which needs to be corrected.

Figure 4 shows a comparison of typical spectra predicted by the two algorithms – in this case for the 5m hill at 420m. In the important case of downwind propagation there is general agreement between the shapes of the spectra, but particularly for upwind propagation there are significant differences.

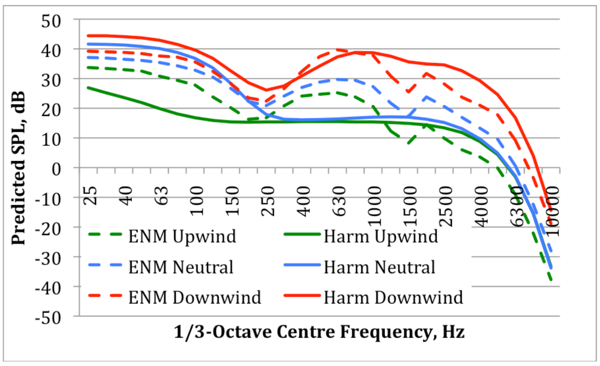

Figure 4 Comparison of SPL spectra predicted by ENM and Harmonoise – 5m hill at 420m.

COMPARISON WITH MEASURED DATA

In 2007 a series of measurements was conducted in the Collie Basin, W.A., aimed at providing reliable measurements of actual noise levels under a variety of meteorological conditions. The study is reported in Herring Storer Acoustics / Wilkinson Murray 2008, and will not be described in detail here. It involved a loudspeaker source producing 1/3-octave bands of filtered pink noise, with measurements at distances from approximately 1,000m – 3,000m, and simultaneous monitoring of meteorological conditions using a tethered balloon.

Attenuations between the speaker and several measurement locations were recorded during 17 periods of approximately 15 minutes on four nights, giving a total of 37 measured 1/3-octave attenuation spectra. These were converted to the total SPL from a dozer spectrum at the measurement location, and compared with predictions from both ENM (as reported in the original study) and Harmonoise. For predictions, the meteorological data used was wind speed at 10m and the measured temperature gradient between 10m and 30m. In keeping with common practice borne of experience, for ENM calculations, wind speeds over 3m/sec were modelled as 3m/sec to prevent excessive over-prediction.

Results are shown in Figure 5.

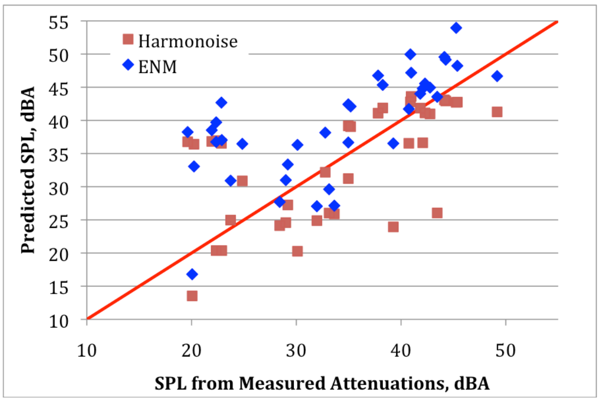

Figure 5 SPL from a dozer spectrum as calculated from measured attenuations in the Collie Basin data, and SPLs predicted by ENM and Harmonoise

The following points are of interest.

1. There are several occasions when both algorithms significantly over-predict the measured noise level. These appear to be occasions when propagation cannot be reliably predicted simply from the bulk meteorological data used in these models.

2. There are several occasions when Harmonoise significantly under-predicts the measured levels. Once again these are conditions under which propagation close to the ground is important in the prediction.

3. For the remainder of the data, ENM tends to slightly over-predict the results, while Harmonoise tends if anything to slightly under-predict.

CONCLUSION

To provide accurate information on noise levels from proposed large-scale industrial operations such as mines, it is essential to be able to model the effects of both terrain and meteorology in a realistic way. Algorithms such as ISO 9613 and CONCAWE do not provide sufficient flexibility to consider meteorology, in particular, as it applies at the specific site in question.

A number of practitioners have used the ENM algorithms for this purpose over a number of years, and have gained sufficient experience to understand how they can be applied, under what conditions they are reliable, and when they may fail. However, as the software underlying the algorithms appears to be reaching the end of its useful life, alternatives are required.

The Harmonoise point-to-point calculation algorithms provide a rigorous and well-considered set of prediction procedures which are designed to allow for multiple calculations under various meteorological conditions. They are open-source, and supported by a group within the European Community. They were developed largely for use in "noise mapping" projects, and in particular for use in modelling road and rail noise, but the "point-to-point" algorithms are based on general physical principles of sound propagation.

However, the comparisons above indicate issues in the use of the unmodified Harmonoise algorithms. If these can be resolved, they could form the basis of an improved calculation procedure, incorporating meteorological parameters derived from models such as TAPM as well as efficient procedures for performing the large numbers of parallel calculations that are required to estimate statistical properties of the noise level distribution.

Based on the above investigations, the following conclusions can be drawn.

- As they are currently coded the Harmonoise algorithms give very counter-intuitive results when dealing with propagation close to the ground, both in terms of the calculated ground attenuation and in deciding when a below-line-of-sight barrier is to be assumed. This should be investigated and hopefully rectified.

- The provided methods of entering meteorological data using tables are not consistent with usual conventions in Australia and are not very consistent with the goal of allowing arbitrary conditions to be entered. An alternative is described in the body of this paper.

- Apart from these issues, the algorithms appear to predict measured noise levels relatively well on average, giving a slightly lower average prediction than ENM. However, it is often desirable to predict the upper percentiles of measured noise levels rather than the average. To do this it may be necessary to incorporate a correction or "safety factor" of 1 – 2 dBA into calculations performed with Harmoise to emulate the predictions generally provided by ENM.

Finally, the C++ source code that encapsulates the Harmonoise algorithms is relatively easy to test, and also to "wrap" in other languages for development of larger programs. This can facilitate the development of both open-source and closed-source code to perform more elaborate functions such as interrogating GIS databases and meteorological models for information, and extracting statistical information from multiple calculations under different meteorological conditions.

Publishing basic point-to-point noise prediction procedures as open-source code, in addition to a detailed mathematical description, is an important step toward achieving comparability of results, and a better understanding of the strengths and weaknesses of various procedures.

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