Proceedings of the Institute of Acoustics

NOISE PROPAGATION AT WIND FARM SITES

J H Bass

Renewable Energy Systems Ltd, First Floor, 11 Elmbank St, GLASGOW, G2 4PB

1. INTRODUCTION

This paper describes an assessment of the performance of various sound propagation models and discusses the appropriateness of their application to potential wind farm sites. The study is based on data obtained by field survey at the Carland Cross and Coal Clough wind farm sites, these data being recorded whilst both were still in a 'green field' state [1].

It should be stressed that rather than an academic study of the physics of sound propagation in complex conditions, with the aim of developing a new propagation model, the emphasis of this work has been to see how well currently available models perform, when used by a reasonably experienced engineer. As a result, the models have, as far as possible, been treated as 'black box' models (although such an approach is not always possible with more complex models).

2. BACKGROUND

Given a statement from a manufacturer specifying a wind turbine's sound power level, to predict the noise levels resulting from a wind farm of such machines at nearby dwellings it is necessary to use a sound propagation model. Given the locations and type of machines, these noise levels will clearly depend both upon the site's topography and the local meteorology. Whilst there are numerous sound propagation models in existence, there is, at present, no standard, widely accepted tool available within the wind energy community to do this.

The model most commonly used is that proposed by the International Energy Agency's (IEA) Expert Study Group [2]. This simple propagation model takes account of sound attenuation due solely to geometrical spreading and absorbtion by air: the effects of topography, ground cover and meteorology are not included. A better approach might be the use of one of the more sophisticated models, for example ENM (Environmental Noise Model), a proprietary software suite developed by RTA Software of Australia. This is a state-of-the-art suite, specifically designed for the prediction of noise levels resulting from multiple noise sources in a complex environment. It is much more detailed than the IEA recommended model and takes account of all the factors mentioned above. The principle advantages in using this model are that it exists already, is flexible, reasonably easy to use, has a large user base, is widely used by noise professionals internationally and should give more reliable predictions. Further, as well as the 'standard' sound propagation algorithms which the suite comes with, it is possible to incorporate a number of different modules containing fully validated algorithms as specified by, for example, CONCAWE, BBN/EEI and NORDFORSK. The main disadvantage is that it requires more detailed input data, and the question is whether the additional effort required is repaid by an improvement in the quality of predictions.

Throughout this paper sound pressure levels are quoted in decibels referenced to a sound pressure of 20μPa and are weighted using the A-network. Sound power levels are in decibels referenced to a sound power of 1pW.

3. EXPERIMENTAL PROCEDURE

3.1 Overview

To assess the models, wind turbine-like noise, with known sound power level, has been broadcast across the two sites and noise level measurements made at a number of surrounding locations, in a range of meteorological conditions. These data have then been compared with predictions from the IEA model and ENM suite. By removing uncertainty about the strength of the source, any differences between predictions and measurements can be identified as due to propagation effects that the models fail to reproduce.

3.2 Methodology

The procedure adopted at both Carland Cross and Coal Clough is essentially identical. White noise from a signal generator is fed into a power amplifier driving a matched loudspeaker. This dodecahedron loudspeaker creates an almost spherical soundfield, up to a maximum sound power level of 117 dB. To calibrate this, ie to determine its sound power level, L_W, the sound pressure level, L_p, a distance R away is measured and a correction for the separation applied. The methodology used for this is that recommended by the IEA Expert Group for measurements made in the near field of a source [2]:

$$L_W = L_p + 10\log_{10}(4\pi R^2) \qquad [1]$$

This clearly implies spherical sound propagation. The procedure was verified in both anechoic and reverberant chambers prior to commencing the study.

As the intention of the study was to broadcast noise with similar characteristics to a real wind turbine, and given that the usual acoustic model for a wind turbine is a point source at hub height, the loudspeaker was mounted on a mobile radio mast and raised to around 30 m. This was then used to broadcast noise with a sound power level of typically 110 - 115 dB. Whilst this is rather louder than most wind turbines, it was decided that by broadcasting the largest possible noise signal the best signal-to-noise (ie background noise) ratio would be obtained. Fig 1 shows the arrangement.

At each site, the mast was located at a central location. Sound level measurements were then repeated with the loudspeaker turned on, and then off, over consecutive periods, at each surrounding location at distances up to 1 km from the tower base. This enabled both the background noise level, L_B, and the background plus broadcast noise level, L_T, to be determined.

Fig 2 indicates the positions at which noise level measurements were made at Carland Cross overlaid on a contour map of the site and Fig 3 the positions used at Coal Clough. (Note. Both figures have been generated using the MAP module of the ENM software suite). To assist in their location these positions were identified on-site by measurement or by the intersection of two or more stone walls/hedges. Comparison of the figures highlights the most significant difference between the sites: whereas Carland Cross is a fairly smooth site with simple topographic features, Coal Clough is considerably more rugged, and exhibits a highly complex topography. As a result, it presents a considerably more testing environment for modelling sound propagation than does Carland Cross.

Weather conditions during the field surveys, eg cloud cover, were noted. In addition, the loudspeaker mast was carefully instrumented so that ambient temperature, vertical temperature gradient and humidity could be determined during data collection. Wind speed and direction data were obtained from data logging equipment previously installed on the sites for the purposes of resource assessment. Such data are important both because background noise is strongly correlated with wind speed, and because wind affects sound propagation. These data were collected as inputs to the more sophisticated propagation models.

3.2 Noise Level Predictions

Given the broadcast sound power level for each experiment, L_W, noise level predictions, L_p, are obtained at each measurement position using each sound propagation models. The total perceived noise level, L_T, at each location is then determined by adding the background noise level, L_B, to L_p as follows:

$$L_T \quad = \quad 10 \log_{10} \{ 10^{L_p/10} + 10^{L_B/10} \} \qquad [2]$$

The predicted noise level, L_T, is then compared with the measured value, L_T, at each location. Predictions of L_p have been obtained from both the IEA model and the ENM software suite - see below.

3.2.1 The IEA Model. The IEA model is based on hemispherical noise propagation over a flat, reflective surface and includes air absorbtion. The sound pressure level a distance R away from a source, $L_p(R)$, with sound power level, L_W, is defined as:

$$L_p(R) \quad = \quad L_W - 10 \log_{10}(2\pi R^2) - \alpha R \qquad [3]$$

where α is the sound absorbtion coefficient [2]. This model contains the implicit assumption that in the 'far' field of a source, ie more than 150-200m away, sound will propagate hemispherically. This is in contrast to eqn 1, seen earlier, which assumes that in the 'near' field of the source sound propagates spherically.

3.2.2 ENM. ENM is a suite of computer programs developed specifically for the prediction of noise in the environment [3,4,5]. Sound power level data can be input for up to 100 sources in 1/3 or 1/1 octave band form. Terrain data can be input via digitised ground elevation data, either in contour form or as simple cross sections. Ground type can be specified, along with meteorological data including temperature, humidity, wind speed & direction and vertical temperature gradient. Noise level predictions can be calculated as either single point calculations, or as contour plots. The authors claim that ENM incorporates the results of the latest research reported internationally and contains the most currently developed, accurate and validated algorithms.

In addition to its native algorithms, extra modules can be obtained for ENM containing other sound propagation algorithms, and for these experiments the CONCAWE & NORDFORSK modules were selected. It is assumed that these are strict implementations of the original standards.

The CONCAWE model was developed by the Oil Companies International Study Group for the Conservation of Clean Air and Water [6]. The principal difference between CONCAWE and the native ENM module is that atmospheric conditions are expressed differently: whereas ENM uses a vertical temperate gradient, CONCAWE uses a combination of the Pasquill Stability Category and a 'sky code'. An important practical difference between ENM and CONCAWE is that where CONCAWE places great reliance on empirical data and has been the subject of an extensive validation exercise, ENM is based more on the latest theoretical knowledge, and has not been as rigorously tested.

The NORDFORSK model is defined by the contents of Technical Report Number 32, published in 1982 by the Lydteknisk Laboratorium and entitled 'Environmental Noise From Industrial Plants: General Prediction Method'. The research was sponsored jointly by Danish Environmental Protection Agency, the Norwegian Environmental Protection Agency and the Swedish Environmental Board. The principal difference between NORDFORSK and the native ENM module is that it ignores the effects of both wind and vertical temperature gradients. It does, however, take into account sound absorption through forest and tall grass. Allowance is made to specify either a summer or winter season, to take into account the reduced attenuation afforded by foliage during winter months.

3.3 The Effect of Wind on Propagation

Use of the IEA model, ENM, CONCAWE & NORDFORSK gives four, distinct, prediction methods. However, as both ENM and CONCAWE, unlike the IEA model or NORDFORSK, can model wind speed and direction effects, and because initial sensitivity tests showed that their predictions were much more sensitive to these than other meteorological conditions, eg temperature gradients, it was decided to make ENM and CONCAWE predictions both with and without wind speed/direction effects included. An added benefit is that the magnitude of such effects will be apparent. This gives an effective total of six prediction methods.

4. RESULTS

As might be expected, given the differing nature of the terrain of two sites, the results are rather different. This was also influenced by the fact than generally stronger winds were experienced during the field survey at Coal Clough than during that at Carland Cross.

Considering the Carland Cross experiments first, Fig 4 shows measured L_{eq} noise levels as a function of distance for a typical experiment at Carland Cross. As can be seen, the noise levels fall rapidly with increasing distance from the source. The figure also shows predictions from the IEA model, ENM & CONCAWE (both with and without wind speed effects) and NORDFORSK. Fig 5 shows these data as differences between the predictions and the measured values.

Several experimental runs were made and similar results obtained for each. For each run the performance of the models were quantified through the root mean square prediction error and greatest absolute prediction error. These data were then pooled and overall RMS errors calculated for each propagation model - the results are shown in Fig 6. These errors are taken to be indicative of the overall performance of the models and are used to rank them. Note that some points have been censored from the process where the data suggests that they were contaminated by extraneous noise, eg from cars, aeroplanes etc.

The following observations/conclusions can be made:

i) NORDFORSK performs best, with both minimum RMS error and minimum greatest absolute error. The results indicate that ≈ 95 % of predictions are within ± 3 dB of the true value.

ii) the IEA model performs almost as well as NORDFORSK, the results suggesting that ≈ 95% of predictions are within ± 5 dB of the true value. In practice, the IEA model generally overpredicts, probably because, unlike the others, it models neither ground effects nor barrier effects.

iii) CONCAWE, both with and without wind effects, performs better than ENM, but worse than NORDFORSK or the IEA model. The inclusion of wind effects marginally improves CONCAWE predictions, but noticeably degrades ENM's performance - ENM is clearly more sensitive to wind than CONCAWE. It is interesting to compare these errors with results from a previous assessment of ENM [7]. This study found that 74% of ENM predictions were within ± 3 dB of the true value and 94% were within ± 4.9 dB. These results are significantly better than those achieved here.

iv) The poor performance of ENM, together with its cost, cast doubt on its adoption as a standard tool. At the distances of relevance for wind farm applications NORDFORSK, and even the IEA model, perform significantly better. As these exist in the public domain and are freely available, they are better choices. The IEA model, in particular, has the advantage of being easy to implement, providing a low cost route to good predictions: this would likely result in predictions rather better than those from ENM or CONCAWE. NORDFORSK would, however, be preferred.

Fig 7 shows measured L_{eq} noise levels as a function of distance for a typical experiment at Coal Clough. Also shown are IEA, ENM & CONCAWE (with & without wind effects) and NORDFORSK predictions. Fig

8 shows these data as predictions errors and Fig 9 the overall RMS errors for each model calculated from the pooled data. As before, these RMS errors are taken to be indicative of performance.

Inspection of these figures shows that:

i) the model predictions are all significantly worse than those obtained at Carland Cross, typically three times worse, and lie in a range from around - 5 to + 15 dB about the true values. Unlike previously, the predictions are positively skewed, ie they are biased above, rather than either side of, the true values. The likely explanation is a combination of poor modelling of barriers - the complex nature of Coal Clough's topography is likely to play a significant part in sound attenuation - and poor modelling of wind effects, particularly in high winds.

ii) The performance ranking of the models is completely changed, with ENM (with wind effects) giving both minimum RMS error and minimum greatest absolute error. The results suggests that ≈ 95 % of predictions should lie between ± 12 dB, and comparing this with those suggested above, it is clear the results are even further outside the targets claimed [7].

iii) ENM (no wind effects) and NORDFORSK perform almost identically well, both being slightly worse than ENM with wind effects. Given that NORDFORSK also performed best at Carland Cross, this suggests that it might be the best model to use.

iv) the inclusion of wind effects markedly improves CONCAWE predictions. Unlike previously, CONCAWE seems equally sensitive to the inclusion of wind effects as ENM. This probably reflects the generally stronger winds experienced during this study than previously.

vi) the IEA model performs worst, giving RMS errors almost twice as great as ENM (with wind effects). The predicted noise levels all significantly overpredict the measured data, leading to prediction errors of 10 dB and more. This highlights the limitations of a 'non-modelling' approach to sound propagation.

5. THE PROPAGATION & AUDIBILITY OF TONES

Manufacturers often claim that although wind farm noise may have an audible tonal content in the near field, such tones will not be audible in the far field, ie at the closest habitation. There is little data available to substantiate this claim, however, and as the two most relevant standards for the assessment of wind farm noise, BS 4142 and the Danish Statutory Order, both include a 5 dB penalty for tones, it remains an area of potential risk for the developer [8,9].

Using the equipment described above, but with the addition of signal generators and a mixer, noise, with a tonal content similar to that of a modern wind turbine, has been broadcast across both sites. By measuring narrow band noise spectra at increasing distances from the source the prominence of the broadcast tones have been quantitatively assessed using the Joint Nordic method [10]. This is an objective method for assessing the human perception of tones and is based on the psycho-acoustic concept of critical bands [11]. In outline, the tone level is compared with that in a critical band about the tone, the width of which is defined by the tonal frequency. The difference is used to rate the tone's audibility.

Fig 10 shows an example of typical results obtained from such an experiment at Coal Clough. This clearly shows that both tone and critical band levels attenuate at the same rate, the difference between them remaining virtually constant, independent of distance. This implies that tones present in the emission of a wind turbine will remain so into the far field, becoming inaudible only when masked by background noise. Clearly the point where this occurs will be influenced by distance from the source and, in practice, is likely to occur at distances exceeding 200 - 300m. This underlines the importance of background noise surveys, to ensure that masking levels are sufficient prior to the construction of wind farm developments.

6. DISCUSSION & CONCLUSIONS

This study has shown that there is a marked divergence in the performance of the sound propagation models assessed in a low wind speed/simple terrain scenario and in a high wind speed/complex terrain scenario. At Carland Cross, the best model (NORDFORSK) gave RMS errors of ≈ 2 dB and the worst (ENM + W) ≈ 4 dB, whereas at Coal Clough the best model (ENM + W) gave errors of ≈ 6 dB and the worst (IEA) ≈ 11 dB, three times greater. The investment of effort required to obtain predictions from even a simple model, like the IEA model, is considerable, and for the more complex models, particularly those run from within the ENM framework, the investment is even greater, especially if complex terrain data needs to be generated. Given the magnitude of both the RMS and greatest absolute errors obtained in this carefully controlled experiment, it would appear that none of the models repay this investment with more reliable predictions. When the models get 'stressed' by conditions in which propagation is difficult to model, none are able to cope. This is unfortunate, as it is in just these conditions that wind farm developers are interested.

Whilst none of the models perform well, it could be argued that other propagation models, eg Raynoise, ISO 9613 etc, might perform better. This is unlikely, as there are factors which mitigate against any theoretical model performing well in such testing conditions. For example:

i) although suites like ENM attempt to model the effect on propagation of complex phenomena such as wind speed and direction, temperature gradients, humidity, temperature etc, with more or less success, to do this correctly means that such conditions must be accurately known. On typical wind farm sites, such conditions are unlikely to be known, nor are they likely to remain stable for more than short periods. Even if such models reproduced these real-world effect perfectly, the complex and dynamic nature of these variables, on second by second timescales, would mean that values chosen for use at one point might not be appropriate seconds later.

ii) regardless of how predictions are obtained, they must be added to either indicative, or measured background levels to arrive at the total perceived level. As developers are mostly interested in noise immission levels at nearby neighbours, and as these are usually several hundred metres away from the nearest turbines, the predicted levels will usually be of similar magnitude to the pre-existing background at those locations. Even in fairly constant winds such background levels can be highly variable, so that when the two are added (see eqn 3), detail in the prediction may be swamped, entirely negating the benefit of a sophisticated model. This effect can be seen at both Carland Cross and Coal Clough: as the broadcast noise levels fall to the existing background levels, ie as the distance increases from the source, the measured L_T become increasingly affected by elements of the background. The high degree of variability in both the broadcast and background noise is evidenced by the large difference between the L_{eq} and L_{90} noise levels.

It could reasonably be argued that the experiments described in this study are unfair because the models have been used in conditions where they couldn't be expected to perform well, ie in complex terrain, gusty winds and high and variable levels of background noise. If this is the case, and for wind farm sites generally it may well be, then why use them? My simple minded conclusion from these results is that these are entirely the wrong sort of models to use. As well as being expensive to purchase, and involve considerable investment to use, they produce results which are not really what the developer *require*.

To illustrate this, Fig 11 shows a scatter plot of $L_{A90,10\,min}$ noise immission data measured over a period of about a week at a typical nearest neighbour location for a typical UK wind farm. The data are shown as a function of wind speed and are broken down by direction. What developers really need is some idea of the shape of the envelope surrounding such data before they build a wind farm. This could be characterised by the mean value and spread of likely immission values, as functions of wind speed and direction.

A more profitable approach to the modelling of noise immission might lie in the development of a simple empirical model and plots such as Fig 11 suggest how such a model could be developed. As a result of the large number of wind farms currently in operation in the UK, it would be possible to collect a large body of data similar to that shown and, with knowledge of the number, type and positioning of the wind turbines on the site, use these data to develop an entirely empirical model. The development of such an empirical model is likely to be a far more appropriate, engineering-oriented approach to the problem of noise level prediction than the use of any of the currently existing, more theoretical models. Such a model could be specifically tailored to the needs of developers, for example, by providing the information required to perform probabilistic, ie level crossing, analyses.

The mechanism by which tones become inaudible with increasing distance is simply masking by background noise. Field results indicate that tones emitted by an operating wind turbine that are audible in the near field, will remain audible in the far field until masked by background noise, regardless of distances. In practice, for a 'normal' site this is likely to occur at distances in excess of 200 - 300 m.

7. ACKNOWLEDGEMENTS

This study was partially funded by the UK Department of Trade & Industry through the Energy Technology Support Unit at Harwell. The author would like to thank Andrew Bullmore, of Hoare Lea & Partners, Mark Legerton of ETSU and Roger Rodwell of Gracey & Associates for their assistance with this study.

8. REFERENCES

[1] BASS JH (1992), Noise Assessment at Carland Cross Wind Farm Site, In Proceedings of the DTI/BWEA Workshop on Wind Turbine Noise, ETSU Report ETSU-N-123.

[2] LJUNGGREN S & GUSTAFSSON A (1988), Expert Study Group on Recommended Practices For Wind Turbine Testing And Evaluation; 4. Acoustics Measurement of Noise Emission From Wind Turbines, 2 ed, Executive Committee Of The International Energy Agency Programme For Research And Development On Wind Energy Conversion Systems.

[3] ENM - Environmental Noise Model (1989), Publicity Information, RTA Software Pty Ltd, Sydney, Australia.

[4] TONIN R (1984), Estimating Noise Levels From Petrochemical Plants, Mines & Industrial Complexes, Acoustics Australia, Vol 13, No 2, 59-67.

[5] ENM - Environmental Noise Model (1989), User Guide, Version 1.0, RTA Software Pty Ltd.

[6] MANNING CJ (1981), The Propagation of Noise From Petroleum and Petrochemical Complexes To Neighbouring Communities, CONCAWE Report 4/81, Den Haag.

[7] MOLLER I & BROWN R (1991), Application of the Predictive Noise Model ENM at Boyne Smelters, In Proceedings of the Internoise '91 Conference, Australia.

[8] BRITISH STANDARDS INSTITUTION (1990), BS 4142:1990, Method for Rating Industrial Noise Affecting Mixed Residential and Industrial Areas.

[9] NATIONAL AGENCY OF ENVIRONMENTAL PROTECTION (1991), Statutory Order on Noise From Windmills, Ministry of the Environment, Denmark.

[10] KINSLER LE, FREY AR, COPPENS AB & SANDERS JV (1987), Fundamentals of Acoustics, 3 ed, Chichester, John Wiley & Sons.

[11] LJUNGGREN S (1991), Measures Against Mechanical Noise From Large Wind Turbines - A Design Guide, In Wind Energy: Technology & Implementation, Proceedings of the EWEC'91 Conference (ed Van Hulle FJL, Smulders PT & Dragt JB), pp727-731, London, Elsevier.

NOISE PROPAGATION AT WIND FARM SITES

FIGURE 1 Loudspeaker Arrangement

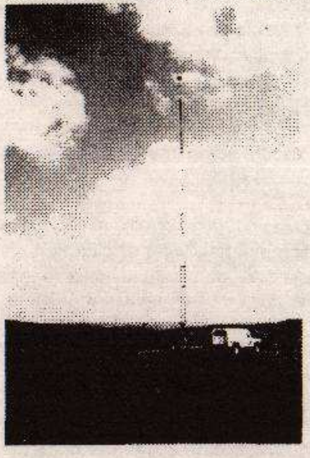


FIGURE 3
Coal Clough Site

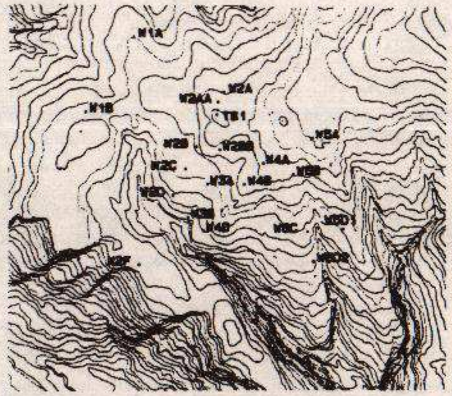


FIGURE 2
Carland Cross Site

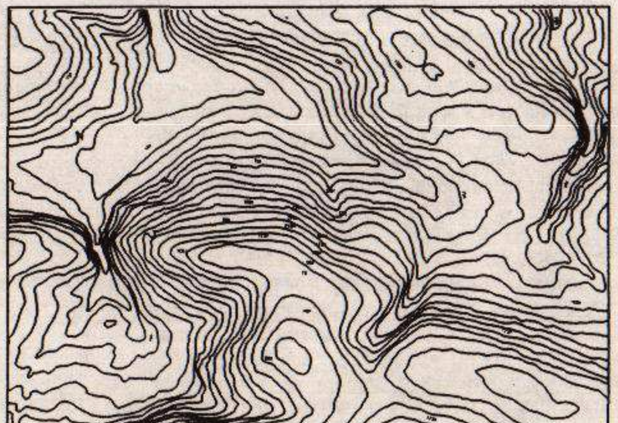


FIGURE 4

Comparison of Predictions & Measurements
(Carland Cross)

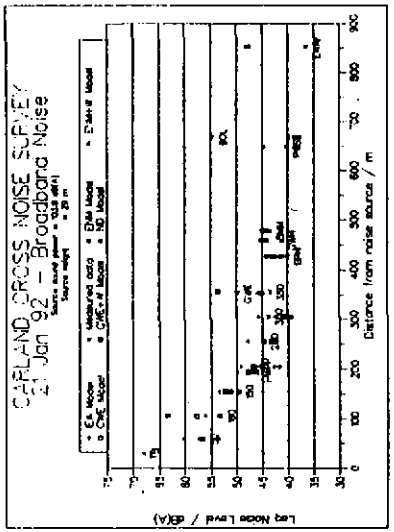


FIGURE 5

Model Prediction Errors

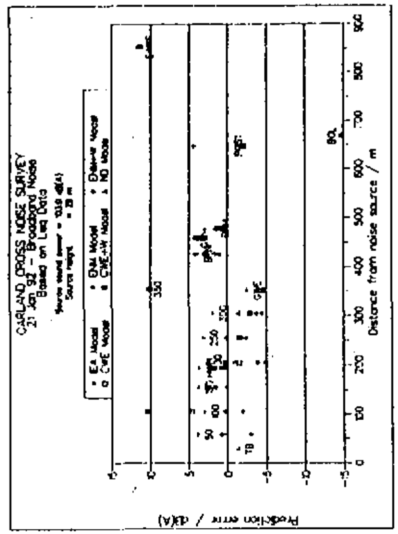


FIGURE 6

Overall Performance Assessment

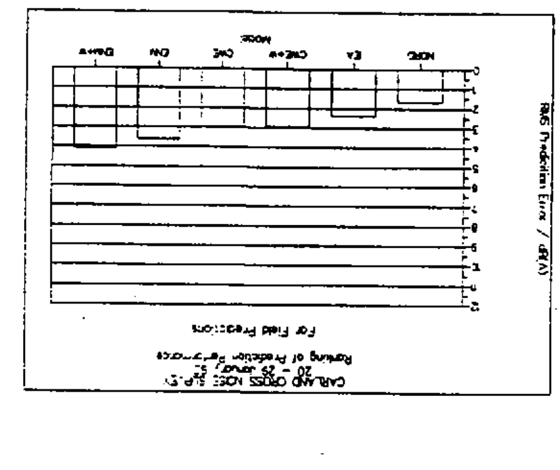


FIGURE 7

Comparison of Predictions & Measurements
(Coal Clough)

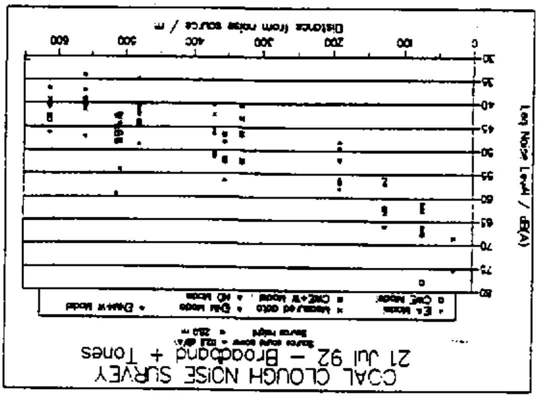


FIGURE 8

Prediction Errors

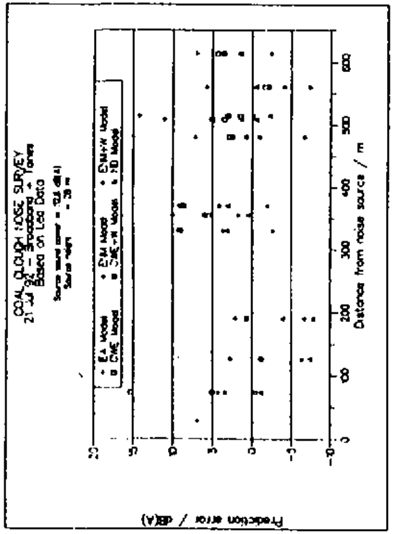
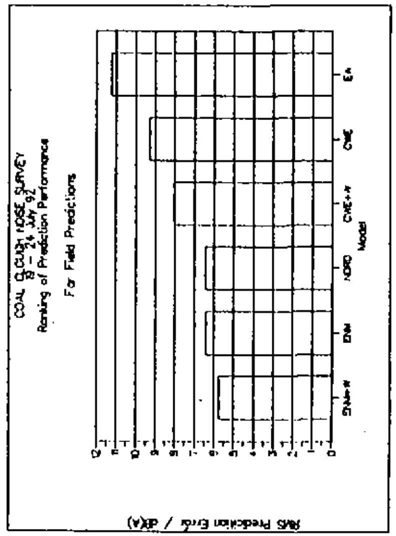


FIGURE 9

Overall Performance Assessment



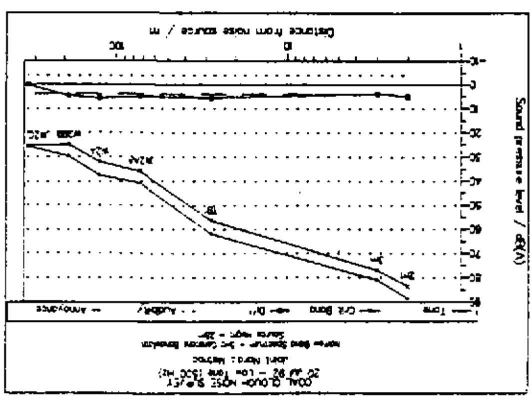


FIGURE 10

Tonal Propagation Data

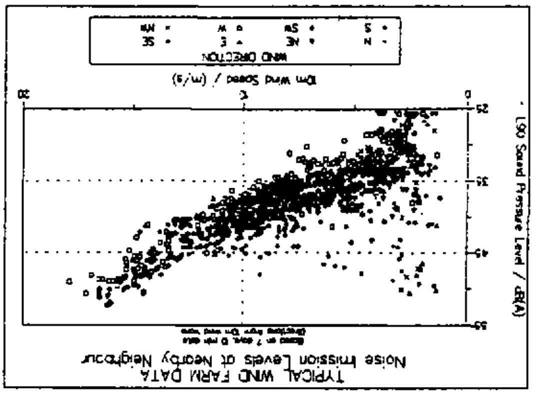


FIGURE 11

Typical Wind Farm Data