Hearing Statement of William Leslie Huson

In the matter of the Conjoined Public Inquiry concerning:

WIN 370-4 Craiginmoddie Wind Farm

WIN 370-5 Carrick Wind Farm

WIN 370-6 Knockcronal Wind Farm

Expert retained on behalf of

Save Straiton for Scotland (SSfS)

NAME AND ADDRESS OF EXPERT

1 William Leslie Huson

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QUALIFICATIONS

6 BSc (Hons) Applied Physics, UK 1975

7 MSc Sound and Vibration Studies, Institute of Sound and Vibration Research, Southampton, UK 1977

PROFESSIONAL AFFILIATIONS

8 Chartered Physicist, UK

9 Member of the Institute of Physics, UK

10 Member of the Institute of Acoustics, UK

11 Member of the Australian Acoustical Society

12 Member of the AV0001acoustics working group for Standards Australia

13 Australian representative for the International Institute of Noise Control Engineers (I-INCE) Technical Study Group 5 *A GLOBALAPPROACH TO NOISE CONTROL POLICY* (Now disbanded after completion of the scope of work defining this group – see http://www.i-ince.org/data/iince061.pdf)

EXPERIENCE

14 Since graduating I have been involved in several scientific areas of research and development. My early experience was in constructing a microwave device to measure the temperature of plasma inside a nuclear fusion experimentation device at the UKAEA, Culham Laboratory in the UK. I then worked in research and development of thermal imaging devices prior to completing my Masters in Sound and Vibration Studies. My work since then (1977) has been primarily associated with acoustics and vibration both terrestrial and underwater.

15 Prior to 1991 I worked as a Sound and Vibration consultant in the UK for 12 years with involvement in a wide range of industries.

16 For the past 33 years I have worked in Australia as a noise and vibration consultant and have operated through my own consultancy firm for the past 27 years. I am experienced in modelling acoustic propagation from a variety of sources such as railways, roads, aircraft, underwater ordnance, wind farms, pile driving, blasting and numerous types of industry.

17 Of relevance to the evidence provided here is the work I completed for the Toora Wind Farm in 2002 which involved detailed analysis of pre and post construction noise data using NZS6808 1998 to check compliance with license conditions. NZS6808 is based upon ETSU-R-97. My experiences in the analysis of wind farm noise data led to a paper that was presented at the joint Australia and New Zealand Acoustics conference in 2006 titled "Review of the Application of NZS6808 to wind farms in Australia." This paper highlighted the sources of error that were implicit and allowed in the NZS6808, 1998 standard and ETSU-R-97. The latest version of the NZS6808 standard (2010) addresses a number, but not all, of the data analysis error concerns described in my paper. ETSU-R-97 and the Institute of Acoustics Good Practice Guide to the Assessment and Rating of Wind Turbine Noise is regularly referenced when interpreting parts of NZS6808 in Australia and I am familiar with this document and the supporting Supplementary Guidance Notes.

18 Over the past nine years I have been independently gathering sound data in the audible and infrasound parts of the acoustic spectrum at numerous wind farms in Australia, the UK and Ireland. A summary of some of this research work on infrasound was presented in a peer reviewed paper: Huson, W. Les. "Stationary wind turbine infrasound emissions and propagation loss measurements." 6th International Conference on Wind Turbine Noise, Glasgow 20-23 April 2015.

19 I have investigated the Preferred IoA Method for the assessment of amplitude modulation (AM) in detail and applied it to several wind farm measurements taken outside dwellings near to numerous wind farms in Australia. The findings of this work are the realisation that the

Preferred IoA Method is only suitable for assessing a single wind turbine, that the resulting AM values greatly underestimate short term peak to trough amplitude modulation levels observed and that the Method is wholly unsuitable to assess AM (peak to trough amplitude modulation) from multiple wind turbines.

20 Detailed analysis of AM from wind farms has revealed that many AM events also exhibit impulsiveness when evaluated according to BS 4142:2014+A1:2019.

OTHER CONTRIBUTORS TO THIS REPORT

21 None

SCOPE OF THIS REPORT

22 The requested scope of this report is to complete a peer review of the Craiginmoddie, Carrick and Knockcronal Wind Farm applications (WIN 370-4, WIN 370-5 and WIN 370-6) and to express my own expert opinion as to whether the Applications should be granted in the terms sought by the proponent, given any noise/vibration issues I may identify.

23 The questions fall within my area of expertise and in preparing this report I have endeavoured for it to be complete and accurate.

GENERAL COMMENTS

24 ETSU-R-97 and the subsequent IoA Good Practice Guide (GPG), that attempts to reduce the interpretation options within ETSU-R-97, are both under review by the UK Government.

25 Although the UK Government has yet to officially respond to a report by WSP on the issue of whether stakeholder parties consider a change to ETSU-R-97 warranted, the WSP report does advise the UK Government that both ETSU-R-97 and the GPG would benefit from further review and update.

26 ETSU-R-97 and the GPG remain open to interpretation and contain technical errors.

27 The Scottish Government has in Policy Statement 2022 recognised that the UK Government may determine that ETSU-R-97 and the GPG may require updating, but in the meantime all wind farm development applications are required to follow current guidance.

28 Given that there are questions raised about the future validity of ETSU-R-97 I submit that any interpretations of the current framework for assessing a wind farm development must err on the side of caution.

29 For example, the GPG acknowledges that a ground absorption factor, G, in section 4.3.4 “is commonly used, as it will tend to provide robust predictions in most situations” but also notes

that the predictions can be too high. It has also been found that predictions can also be too low.

30 Generally, predictions made using 'hard ground' where G=0 have a receiver height of 1.5m in noise models implementing ISO9613-2. However, the GPG recommends the use of G=0.5 combined with a receiver height at a dwelling of 4m.

31 The noise model prepared by TNEI use G=0.5 and 4m receiver height.

32 In practice, all background noise surveys and compliance surveys use a receiver height (microphone measurement height) of 1.5m so it would be reasonable to apply G=0 with receiver height of 1.5m. Doing so will increase all predicted sound levels by approximately 4dB and this cautious approach complies with ETSU-R-97 and the GPG.

33 There are other reasons for using G=0 with a receiver height of 1.5m. The GPG in section 4.1.3 refers to a paper by Evans and Cooper, 2011. This paper states "the ISO 9613-2 method with 50% absorptive ground, can under-predict noise levels in some situations and should only be used with caution.". 50% absorptive ground means G=0.5.

34 Reference is also made to a Joule Study (JOR3-CT95-0091 'Development of a wind farm noise prediction model', Bass J H, Bullmore A J, Sloth E, Final Report for EU Contract JOR3 CT95 0051, 1998), however this study did not recommend the use of ISO 9613-2 and Sloth in his presentation at an AWEA conference in 2004 confirmed that if ISO 9613-2 is to be used then G=0 must be applied to the model.

35 The references given in the GPG do not support the recommended G=0.5 for use in the ISO9613-2 noise model with a receiver height of 1.5m.

36 I recommend that a cautious approach should be used in the noise modelling and that the models must be repeated with G=0 and a receiver height of 1.5m.

37 To gauge if more cautious noise model inputs will have any significant outcome for the proposed three wind farm developments it is simply a matter of adding 4 dB to all predicted sound levels.

38 Other corrections to ISO 9613-2 are suggested in the GPG for barrier attenuation from the terrain and for areas where a 'valley' effect occurs.

39 Table 1 of Annex 4 in the TNEI report "Operational Noise Report, Craiginmoddie Wind Farm", 18 March 2023 lists corrections due to the topographic barrier effect and 'valley' effect that were applied to the noise model outputs. A valley effect attracts a 3 dB penalty and a maximum of -2 dB terrain barrier attenuation is applied where necessary. However, it is noted that where both effects apply that only the -2 dB correction was applied. This is inconsistent with the GPG and a total of +1 dB correction should apply in these circumstances.

40 Table 1 of Annex 4 does not identify where both corrections apply but in these circumstances the predictions in accordance with the GPG are 3 dB too low.

Sound power levels

41 Sound power levels used in the Craiginmoddie wind farm operational noise report, 18 March 2023 for the Dersalloch wind farm (Tables A5.1 and A5.2) are the same as those used in the Knockcronal wind farm Technical Appendix 10.1 Environmental Noise Assessment (Tables C3 and C4). However, these differ from those used in the Carrick wind farm assessment (Tables 9.13 and 9.14).

42 Likewise, for the Hadyard Hill wind farm there are differences between the sound power levels used by one wind farm applicant. For example, Table 9.17 and Table 9.18 of the Carrick wind farm application show test report data and notes that this data has an uncertainty of 1 dB.

43 However, the Craiginmoddie wind farm Tables A5.1 and A5.2 have assumed that the test results include an uncertainty value of 1 dB.

44 The GPG suggests that test results that have a test uncertainty attached should account for expanded uncertainty which is 1.65 times the standard uncertainty of test results.

45 This means that the sound power levels for Hadyard Hill wind farm in the TNEI Craiginmoddie wind farm and Knockcronal wind farm noise predictions are approximately 1.6 dB too low when compared to the Carrick wind farm assessment of sound power levels.

46 It may appear pedantic to investigate details of one or two dB but these discrepancies become important when no margins of compliance are predicted for many dwellings, such as NAL1, NAL5, NAL7 and NAL9.

Background sound levels

47 ETSU-R-97 uses Background sound levels to set the target noise limits applicable for a dwelling. Unrepresentative Background sound levels at integer wind speeds can lead to overly lax noise limits to the detriment of a resident.

48 The Carrick wind farm Environmental Impact Assessment Report (Chapter 9, Noise) relies on Background sound levels measured in accordance with ETSU-R-97 and the GPG. Background sound levels obtained from the Carrick surveys have been used by TNEI in their Operational Noise Report, 18 March 2023 in preference to Background results obtained using a non-compliant ETSU-R-97 and GPG process in the Craiginmoddie noise assessment.

49 The TNEI 18 March 2023 report in Table 5.1 has incorrectly tagged Doughty Farm as being used to set target noise limits based upon Hadyard Hill Extension survey data. The target noise limits refer to data collected from the Carrick survey.

50 The Carrick wind farm Environmental Impact Assessment Report (Chapter 9, Noise) is properly documented with details of the equipment used and a met mast on site, as per the ETSU-R-97 and GPG. This contrasts with the Background survey referenced for the Knockcronal wind farm assessment by Hoare Lea dated November 2021.

51 The GPG requires wind speed data to be measured with an accuracy of +/- 0.2 m/s and +/- 6 degrees wind direction.

52 I have reviewed raw wind speed and noise data used in the Knockcronal assessment and found that the LiDAR and SODAR data regularly missed measurements and cannot be relied upon to meet the measurement requirements of the GPG. The GPG Supplementary Guidance Note 1, section 2.6 cautions about the limitations of LiDAR and SODAR wind speed measurements.

53 No details have been provided on the accuracy of the LiDAR and SODAR systems deployed.

54 The Background data used from the Hadyard Hill Extension wind farm development used a met mast at Hadyard Hill that did not represent wind speed at the Craiginmoddie wind farm site and an attempt has been made to correct this using a process described in Annex 3 of the TNEI report of 18 March 2023. Unfortunately, original survey data was unavailable and Annex 3 does not provide the extent of uncertainty associated with the methods of correction employed or if the method ultimately complies with the accuracy requirements of the GPG.

55 Background survey data obtained whilst other wind farms were operating nearby are described in the Knockcronal and Carrick wind farm noise reports. These reports have applied wind direction filtering to investigate the contributions from the nearest operating wind farms and conclude that they have no influence on the Background data recorded. I disagree.

56 For example, Genoch Cottage has had noise predictions made solely for the influence of the nearest wind farm that is Dersalloch. The optimistically predicted sound level at Genoch Cottage is 30.3dBA at a wind speed of 8 m/s. The measured ‘Background’ level at 8 m/s was 33.4 dBA during the quiet daytime and 32.7 dBA at night. Clearly, one would expect that the Dersalloch wind farm will influence Background sound levels measured at Genoch Cottage when it operates. The operating status of the Dersalloch wind farm at the time of the survey was not provided.

57 If one were to follow the GPG of allowing corrections for Background then the true Background at 8 m/s for the quiet daytime would become 33.4 dB – 30.3 dB which translates to 30.3 dB using logarithmic subtraction.

58 Correction for the true Background at night at Genoch Cottage is not possible due to the arithmetic difference being only 2.4 dB, but it can be expected that the long-term average ‘Background’ noise level measured is dominated by sound from the Dersalloch wind farm.

Noise Sensitive Receptors (NSR)

59 The three noise assessments acknowledge in the Statement of Agreed Matters, 21 March 2023, that only a sample of dwellings in the area surrounding the proposed wind farms have been assessed but that these are representative to assess if the three projects should be approved.

60 However, ETSU-R-97 target noise limits are suggested to protect sleep and the outdoor target noise level of 43 dB was determined after assuming a noise reduction correction for sound outdoors to indoors in a bedroom with an acceptable target sound level in the bedroom of 30 dBA, Leq.

61 Temporary accommodation such as a motel would be considered a NSR but so would a camp site.

62 The target outside noise limit to protect sleep for a tent will be the same as the indoor sleep protection level because a tent does not attenuate sound significantly.

63 I have briefly checked online for camping and caravan sites in the area and note that the area does have camping sites. For example; The Walled Garden Caravan and Camping Park near Kilkerran (30 U, 394361 E, 6128996 N).

64 This NSR would attract a target base noise limit of 30 dBA, Leq or 28 dBA, L90 in accordance with ETSU-R-97, and an assessment of noise impact for such places should be included in each of the three wind farm proposals.

Impact on Tourism

65 I consider that tourists using camping and caravanning sites in the area will be adversely affected.

INFRASOUND, LOW FREQUENCY SOUND AND VIBRATION

Infrasound

66 Measurements of infrasound emissions at the Macarthur wind farm are described in Huson (2015). It was found that overall infrasound levels below 8 Hz changed little for the V112-3MW wind turbines, which are smaller than the candidate wind turbines proposed for these Projects, when the wind farm was completely shut down from maximum power generation in high winds to a standstill in the same winds due to a substation fault.

67 Indoor measurements were also shown in this paper for the wind turbine off/on (start-up) operation at Cape Bridgewater. At Cape Bridgewater the wind turbines are smaller and the residual infrasound was not so apparent when the turbines stopped rotating. The overall infrasound level below 6Hz increased by over 20 dB after start-up of the Cape Bridgewater wind turbines. This finding shows a very large and noticeable increase in the wind turbine

blade passing frequency signature and has no equal in the ambient infrasound environment near to the coast or inland.

68 Accordingly, I disagree with Section 3 of the Statement of Agreed Matters, 21 March 2023 regarding infrasound from wind turbines being comparable to the normal ambient environment and that A-weighted sound levels present sufficient control over the potential impact of low frequency noise.

69 The issue associated with the larger wind turbines is that they emit resonant infrasound tones in the presence of wind even when they are not rotating. This makes it impossible to assess the ambient infrasound levels around the wind farms until after they are decommissioned and removed. I presume that the same will apply for the candidate wind turbines used as examples in the three wind farms of this conjoined inquiry.

70 If ambient infrasound levels are deemed to be important it would be wise to collect samples before construction of the proposed developments, so that ambient infrasound measurements can be compared to when the developments are operational.

71 The effects of infrasound from wind turbines on health have yet to be evaluated properly, a situation that the latest World Health Organisation recommendations on noise recognises. The Australian National Health and Medical Research Council (NHMRC) and the findings of a Senate Committee Inquiry: "The social and economic impact of rural wind farms" June 2011 have reached the same conclusion and a tender with a value of AU$3,300,000 has recently been let by the NHMRC to conduct such missing research into the possible link between wind farm generated infrasound and health. The research project was awarded to two universities in Australia. The researchers have yet to produce a final report of their findings.

72 This research is ongoing and one of the published papers in 2019 by researchers at Flinders University (Nguyen, D. P., Hansen, K. et al. Wind farm infrasound detectability and its effects on the perception of wind farm noise amplitude modulation, Acoustics 2019) stated in its conclusions that: "Overall these preliminary results suggest that WF noise complaints could potentially be governed to some degree by the presence of infrasound" and that " We found that self-reported noise sensitive individuals can detect the presence of low-level infrasound (48 ± 2 dB(G)) above chance."

73 The finding that infrasound at levels of 48 +/- 2 dB(G) can be observed by individuals is in stark contrast to the generally used limit of perception, which suggest that a conservative human perception threshold of 85 dB(G) might be appropriate to account for variations in sensitivity of human hearing.

74 Another recently published paper ("The Health Effects of 72 Hours of Simulated Wind Turbine Infrasound: A Double-Blind Randomized Crossover Study in Noise-Sensitive, Healthy Adults" https://doi.org/10.1289/EHP10757) used constant amplitude synthesised wind farm infrasound but could not reproduce the fundamental blade pass frequency component in the laboratory. The conclusion further notes that "This study suggests that the infrasound component of WTN is unlikely to be a cause of ill-health or sleep disruption, although this observation should be independently replicated."

75 A paper by Cooper, S. ("The use of synthesised or actual wind turbine noise for subjective evaluation purposes" PROCEEDINGS of the 23rd International Congress on Acoustics 2019) is critical of the use of synthesised wind farm infrasound signals and has noted that it was the change in amplitude of the infrasound signal that was observed to be a significant factor in subject disquiet.

76 Unfortunately, the issue of adverse health effects from wind farm generated infrasound remains contentious and this Inquiry may wish to consider an appropriate condition if the ongoing Australian, or other relevant international research, finds adverse health effects from infrasound.

77 Footnote 9 in the Statement of Agreed Matters, 21 March 2023 refers to infrasound from wind turbines and suggests that measurements of infrasound must comply with the sound level meter standard IEC 61672-2:2013+AMD1:2017. This IEC standard is totally unsuitable for the type approval of infrasound measurement instrumentation because it is designed only for the audible frequency range and has an acceptable tolerance of +3dB to minus infinity at 10 Hz for Class 1 sound level meters.

Low Frequency Noise

78 The Statement of Agreed Matters, 21 March 2023, does not consider low frequency sound or infrasound from the proposed three wind farms to be of any concern, citing the WSP BEIS report for its information.

79 However, measured tones around 14 Hz inside a home 2km from two MM82 2MW wind turbines, that are caused by the wind turbines, are accentuated by room resonances (Huson, 2015).

80 The owners have vacated this recently built brick veneer property citing unacceptable health problems believed to be caused by the two wind turbines.

81 Low frequency noise can be generated by a wind turbine. It is not uncommon for a generator input shaft rotation tone to be modulated by the blade pass frequency of the rotor.

82 Recent measurements (2022) of a wind farm comprising Vestas V136 4.2 MW wind turbines exhibit tonal audible characteristics around 150 Hz. This frequency is within the frequency range of DEFRA NAN-R45 and would also qualify as a tonal penalty for measurements outside in accordance with ETSU-R-97.

83 Compliance noise measurements were taken at a wind farm with Vestas V126 3.6 MW wind turbines. The measurements showed tonality, which means there were specific tones that were present. Despite the manufacturer's assurance during the planning phase that the wind turbines would not exhibit these tones, the measurements revealed that they did. As a result, penalties were necessary for the observed measurements at the nearby dwellings. The tones observed were present in the low frequency range covered by DEFRA-NAN-R45 and were also observed outside the dwellings in accordance with the ETSU-R-97 measurement methodology that would qualify for an added tonal penalty.

84 Indoor measurements at Cape Bridgewater were compared to acceptable levels recommended by DEFRA in NAN-R-45. It was found that a tone at 31 Hz, modulated by the blade pass frequency of the rotor, showed an unacceptable level of indoor sound caused by the Cape Bridgewater wind turbines. The Cape Bridgewater Wind Farm has no low frequency noise compliance target.

85 The use of A-weighted sound levels for the assessment of a wind farm will not quantify infrasound or low frequency noise impacts correctly.

86 Unfortunately, low frequency sound and infrasound are a common feature of modern wind turbines.

87 I recommend that a condition requiring compliance with DEFRA NAN-R-45 (recommended indoor levels of low frequency sound) be adopted for these wind farm developments at any NSR to protect occupants from excessive low frequency sound, that is known to be caused by some wind turbines.

Vibration

88 I agree with the comments in the three submissions regarding low levels of ground borne vibration inside homes near wind farms.

89 However, it has been postulated by Kelly (1982) that lightweight building structures can be excited by infrasound pressure from wind turbines and can be one of the major causal agents responsible for the annoyance of nearby residents. Part of the conclusions in Kelly's paper follows:

"In this paper we have presented evidence to support the hypothesis that one of the major causal agents responsible for the annoyance of nearby residents by wind turbine noise is the excitation of highly resonant structural and air volume modes by the coherent, low frequency sound radiated by large wind turbines. Further, there is evidence that the strong resonances found in the acoustic pressure field within rooms actually measured indicates a coupling of subaudible energy to human body resonances at 5, 12 and 17-25 Hz, resulting in a sensation of whole-body vibration. The audible sounds indoors associated with the impulsive excitation of the structure appear to be due to the coupling of energy from the higher frequency discrete bands in the impulse to higher frequency room resonances related to the air volume itself."

90 My own measurements of infrasound inside residences near Macarthur and Cape Bridgewater show infrasound pressure levels similar to those measured by Kelly in 1982. Infrasound causing whole-body vibration is a plausible explanation for the commonly reported symptoms described by residents living near to wind farms.

91 Huson (2015) also covers the propagation of infrasound so that the 'vibration' experienced in homes by people near a large wind farm can be estimated. Infrasound levels can vary significantly over a short time period (seconds) depending upon the phase relationships between each turbine rotor and with local wind speed variations.

92 Infrasound measurements from a residence located 5.4km away from the nearest turbines in the Macarthur array of 140 V112-3MW units and 1.3km away demonstrate very little infrasound attenuation in the near field and that the infrasound levels at this distance (5.4km) are comparable to those reported by Kelly(1982).

AUDIBLE CHARACTERISTICS IN ACCORDANCE WITH ETSU-R-97

Tones

93 It is notable that the proposed candidate wind turbines are assumed not to emit tonal sound.

94 In my experience many wind turbines do emit tonal sound and <u>in the absence of test results proving otherwise then an appropriate penalty should be added to any noise prediction.</u>

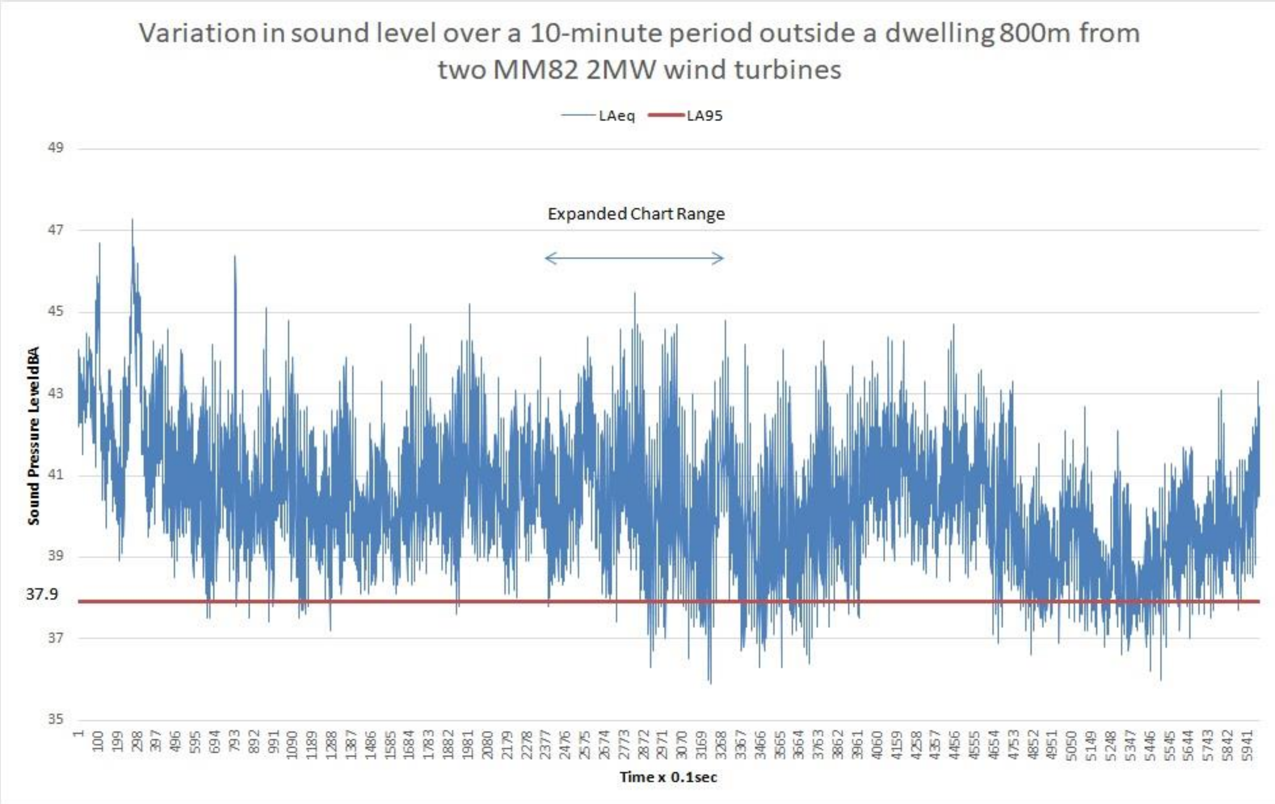
Amplitude Modulation (AM)

95 ETSU-R-97 incorrectly addressed amplitude modulation and made a sweeping assumption that such a characteristic was rare in modern wind farms. This is not the case and it is now recognised that amplitude modulation is the most significantly intrusive sound characteristic of wind turbines.

96 The GPG refers in section 7.2 to ongoing research. Since the publication of the GPG there has been much ongoing research and amplitude modulation is known to be a significant concern for residents near modern wind farms.

97 The following figures illustrate A-weighted sound levels over a 10-minute period that have been recorded at a rate of ten samples per second 800 m from two MM82 2MW wind turbines outside a dwelling.

98 The measurement was taken when the wind turbines were operating in the early hours of the morning when there was no extraneous insect, bird or animal sound but there was sound from wind in trees and foliage. This was confirmed by listening to the audio recordings taken at the same time.

99 

100 Figure 1

101 An expanded range from Figure 1 is shown in Figure 2 to provide more detail.

102 The repetitive variation in sound level is caused by sound from the two wind turbines as the blades rotate.

103 Sound caused by wind in trees and foliage is random, not repetitive as shown in these two charts.

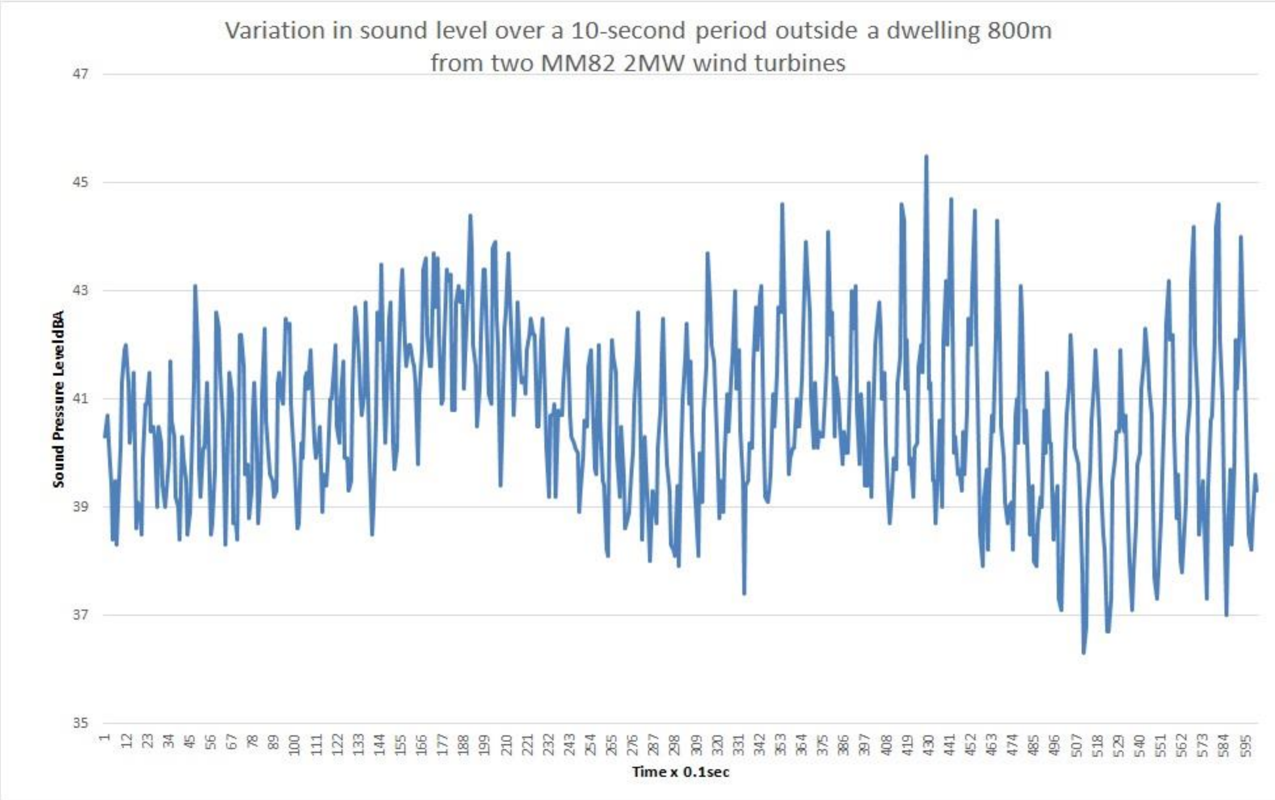
104 Each peak and trough repetition can be linked to each time a blade passes through a part of the swept area.

105 As each wind turbine operates independently of others the small difference in rotation speed between these two wind turbines is causing the peak and trough repetitions to combine yielding a trace that can appear to synchronise at blade passing repetition to the time when the blades are out of synchronisation yielding an apparent doubling of the blade passing repetition.

106 For a wind farm containing many wind turbines the peak and trough level and repetitions vary randomly.

107 However, when synchronised the sound levels add together to produce an overall higher sound level compared to when the individual turbine blades lose synchronisation.

108



109

110 Figure 2

111 Figure 2 clearly shows this for two wind turbines where the first part of the 10-second chart shows the turbines to be out of synchronisation with a generally lower sound level variation peak to trough compared to later in the chart where the turbine blade rotations synchronise causing higher overall peak to trough sound level changes.

112 An unfortunate disadvantage in using the L90 statistic is that the character of sound level changes during any 10-minute measurement are lost and sound level variations are greatly underestimated.

113 A common observation of unusual sound level change occurs when ‘whump’ or ‘thump’ are described by observers.

114 Whump and thump are thought to originate from the aerodynamic sound of wind turbine blades when they encounter wind turbulence or are incorrectly adjusted for the incoming wind that causes a blade to stall temporarily.

115 The occasional whump and thump sounds are much louder than normal wind turbine sounds and the fact that they would not occur for more than 9 minutes in any 10-minute recording means that the L_{A90} centile would not identify such events.

116 Sound levels vary throughout the measurement period in the 10-minute duration of the chart above (Figure 1) ranging from a maximum level of just over 47 dBA to a minimum level of about 36 dBA. From the 6000 sound level samples the single statistical L90 parameter obtained from this chart is 37.9 dBA, shown as a red line across the chart.

117 The L90 centile is only sensitive to the lowest 10 % of sound levels within any 10-minute sample. For example, in the chart above there could be sound levels that reached 100 dBA for many minutes that will have no bearing on the calculated L90 value of 37.9 dBA.

118 A report[1] was prepared for DEFRA that outlines a wind farm noise statutory nuisance complaint methodology. Section 5.4.5 of this report (NAN-R-277) explains the difference between a centile statistical noise metric such as an L90 and the energy averaging Leq as follows:

> "5.4.5 Noise Indices
>
> By convention wind farm noise in the UK is measured using the LA90,10 minute noise index, as it is argued that this index minimises the influence of extraneous noise. However, excepting ETSU –R-97, there are few if any standards that set noise limits using this index. Additionally, it is argued that because the LA90,10min index focuses on the quietest periods in the measurement period it is relatively insensitive to rapid fluctuations in noise level where the noise varies rapidly over a short period e.g. as with aerodynamic/amplitude modulation, and the impact of such characteristics can be underestimated using the LA90,t noise index.
>
> However, elsewhere in the world the LAeq,t index is preferred for wind turbine noise. Use of the LAeq,t or derivatives for environmental noise measurement is recommended by international standards and bodies e.g. ISO 1996 and the WHO, and British Standards such as BS 4142, BS 7445 and BS 8223. Additionally, there are a range of standards and guidance that offer guideline and recommended values of LAeq.T noise levels against which to weigh any measurement. The energy averaging nature of this index means it tends to be biased towards the highest noise levels that occur during a measurement. The figure below shows an indicative sound pressure level trace of a time varying noise signal (SPL) and the approximate LAeq,t and LA90,t values.

[1] NANR277 "Wind farm noise statutory nuisance complaint methodology DEFRA (2011)

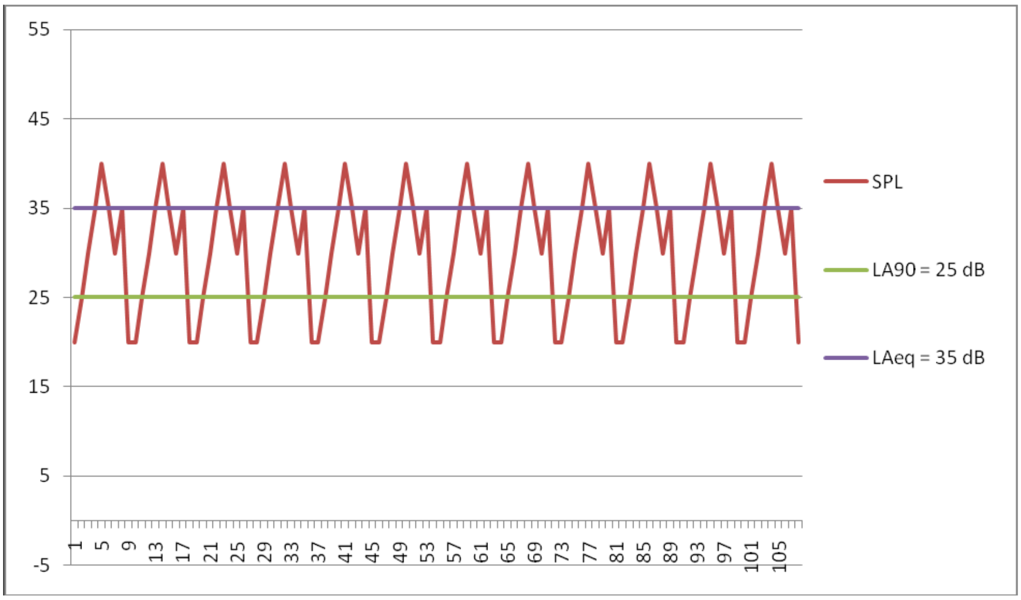
119 

Figure 13 $L_{Aeq,t}$ and $L_{A90,t}$ values of an indicative time varying noise signal"

120 The GPG also explains in section 7.1 that the guide cannot provide a definitive set of conditions for a wind farm, despite suggesting some options.

121 The Reporter should note that there is a current noise condition in force for the Denbrook wind farm that addresses AM limits, as follows:

122 "Condition 20

At the request of the local planning authority following receipt of a complaint the wind farm operator shall, at its expense, employ a consultant approved by the local planning authority, to assess whether noise immissions at the complainant's dwelling are characterised by greater than expected amplitude modulation. Amplitude modulation is the modulation of the level of broadband noise emitted by a turbine at blade passing frequency. These will be deemed greater than expected if the following characteristics apply:

(a) A change in the measured $L_{Aeq,\ 125\ milliseconds}$ turbine noise level of more than 3 dB (represented as a rise and fall in sound energy levels each of more than 3 dB) occurring within a 2 second period.

(b) The change identified in (a) above shall not occur less than 5 times in any one minute period providing the $L_{Aeq,\ 1\ minute}$ turbine sound energy level for that minute is not below 28 dB.

(c) The changes identified in (a) and (b) above shall not occur for fewer than 6 minutes in any hour.

Noise immissions at the complainant's dwelling shall be measured not further than 35 m from the relevant building, and not closer than within 3.5 m of any reflecting building or surface, or within 1.2 m of the ground."

123 If approved, I suggest that Condition 20 of the Denbrook Wind Farm be included as a condition for each of the three wind farms that are the subject of this inquiry.

NOISE PREDICTIONS

124 Without an understanding of the uncertainty of measurement and limitations of equipment and models, apparently detailed technical analysis work can lead to misleading conclusions.

125 No uncertainty analysis has been included in the three wind farm applications

126 The issue of uncertainty has been investigated in: Hansen, K.L, Zajamsek, B., Hansen, C. H.:"Wind Farm Noise Uncertainty: Prediction, Measurement and Compliance Assessment" Acoust Aust (2018) 46:59-67 (https://doi.org/10.1007/s40857-017-0114-7) that covers the use of ISO9613-2 and quantifies the uncertainty of this model.

127 It is generally accepted that ISO9613 is a poor model to use for predicting wind farm sound levels and that it requires several adjustments before reasonably accurate results can be obtained and only in these circumstances may an accuracy of +/-3dB be achieved. ISO9613-2 lists the accuracy of the model to be +/- 3dB at distances up to 1000m for an average source height to receiver height no higher than 30m.

128 Input data to the ISO9613 noise model has been suggested for candidate wind turbines . The sound power data for these wind turbines appear to be a manufacturer's specification rather that test results according to IEC61400-11.

129 Sound power levels for wind turbines should be measured in accordance with IEC61400-11.

130 Inaccuracies from the IEC61400-11 measurements translate into uncertainties in model predictions. The generally accepted uncertainty with the IEC61400-11 measurement is 2 dB for controlled conditions such as minimal inflow turbulence to the rotor.

131 Sloth(2004), a Vestas wind turbine manufacturer employee and co-author of the Joule study, suggested that IEC61400-11 "is a fairly good tool for verification of warranties, but not a good tool for predicting noise at imission points where people actually can get annoyed".

132 Sloth also advises that if the ISO9613-2 noise model is used then hard terrain (G=0) should be used and that installed sound power results from measurements using IEC61400-11 should be corrected for actual inflow angles, actual air density, actual wind shear and actual turbulence intensity, each being known to influence the sound emission of a wind turbine.

133 The three wind farm assessments have used a value of G=0.5 for the ISO 9613-2 noise model stating that such a choice of input will marginally over-predict noise levels to account for potential uncertainty. The ISO9613 noise model will predict typically 4 dB extra noise at imission points 1.5 m above the ground around the Project sites if G=0 is used in the noise model instead of the G=0.5 value used in the three assessments with receiver height of 4m.

134 All measurements of noise use a height of 1.5 m in accordance with ETSU-R-97.

135 The use of a measurement height of 4 m for input to ISO9613-2, is inappropriate. Indeed, the GPG states that: "a ground factor of G=0.0 is commonly used, as it will tend to provide robust predictions in most situations."

136 The implications of this minor correction to the noise models are significant when a compliance margin level of only 0dB is predicted for a number of dwellings.

SUBSTATIONS

137 The treatment of these issues is acceptable in the applications. However, substation noise emissions can cause room resonances that could disturb neighbours.

138 <u>If the DEFRA NAN-R-45 recommended indoor low frequency noise targets are applied in conditions for the ongoing operations of the Project for all sound sources (with the exception of short-term construction activities) then adverse impacts from room resonance effects can be managed</u>.

WIND SPEED DATA

139 Wind speed data accounts for half of all the data required to assess a wind farm using ETSU-R-97.

140 Wind speed data used for the assessment of Background noise levels for the Craiginmoddie and Knockcronal Wind Farms are suspect and do not comply with the GPG.

141 The ETSU-R-97 evaluation process requires an accurate synchronisation of each 10-minute Background sound level to be compared with wind speed which is representative of that on the wind farm site where the nearest wind turbines are proposed to be constructed to a NSR.

142 Background data for the Carrick wind farm application has used the correct evaluation process but there are concerns that the results have been influenced by sound from other operating wind farms nearby.

143 The Knockcronal wind farm application has used suspect wind speed LiDAR and SODAR data that is not robust and may not comply with the accuracy requirements of the GPG.

144 The Craiginmoddie wind farm application has used wind speed data from an unrepresentative location on another wind farm and attempted to correct this data.

145 The correction process is not part of ETSU-R-97 or the GPG and in all probability will exceed the required tolerance for wind speed data that is +/-0.2 m/s in the wind speed range from 4m/s to 12 m/s.

SUMMARY OF OPINIONS

146 The three wind farms have a zero margin of compliance with ETSU-R-97 when operating together.

147 The margin of compliance at NSRs will not be met if the candidate wind turbines exhibit SAC or if the manufacturers specification of sound power level is exceeded in practice.

148 Sound power levels assessed in accordance with IEC 61400-11 do not account for site effects that can increase sound power levels in practice.

149 Sound power levels used in the assessments may not have included the correct margin of uncertainty required by the GPG and if applied correctly would demonstrate non-compliance.

150 Uncertainty of the wind speed data used for the Craiginmoddie wind farm application must be provided to demonstrate that the corrected wind speed data used in the Background evaluation is accurate to +/-0.2 m/s in the wind speed range from 4m/s to 12 m/s.

151 Uncertainty of the LiDAR and SODAR equipment used for the Knockcronal wind farm Background noise assessment must be provided to demonstrate compliance with the required accuracy of +/-0.2 m/s in the wind speed range from 4m/s to 12 m/s.

152 NSRs include at least one camping and caravanning site but this site and any other similar sites in the area have not been assessed.

153 The target noise limits from ETSU-R-97 are too high for an occupier of a tent or caravan to achieve undisturbed sleep. I suggest that the target noise limit for a camp site is 30 dB, LAeq (as per World Health Organisation recommendations) and that any such site must be evaluated accordingly in each assessment for the three wind farms.

154 Low frequency sound is not considered separately in ETSU-R-97 and I propose that a condition be included in a permit, if approved, to assess low frequency noise in accordance with DEFRA-NAN-R45.

155 Infrasound remains an area of contention and any permit for wind farm developments should include a provision that; if it is demonstrated that infrasound from wind farms have an adverse effect on health that the wind farms must comply with such infrasound level limits that prevent adverse health effects.

156 Excess amplitude modulation has been shown to be common near modern wind farms but prediction of this form of SAC is currently not possible. If the wind farms are permitted then a condition should be included in any Permit that provides an appropriate limit for amplitude modulation. Such a condition is already in force at the Denbrook Wind Farm as Condition 20 and this should be included for each of the proposed wind farms, and be renumbered appropriately.

157 I recommend that a cautious approach should be used in the noise modelling and that the models must be repeated using G=0 and a receiver height of 1.5m.

158 A valley effect attracts a 3 dB penalty and a maximum of -2 dB terrain barrier attenuation is applied where necessary. However, it is noted that where both effects apply that only the -2 dB correction was applied. This is inconsistent with the GPG and a total of +1 dB correction should apply in these circumstances.

159 I consider that tourists using camping and caravanning sites in the area will be adversely affected.

160 If ambient infrasound levels are deemed to be important it would be wise to collect samples before construction of the proposed developments, so that ambient infrasound measurements can be compared to when the developments are operational.

161 Many wind turbines do emit tonal sound and in the absence of test results proving otherwise then an appropriate penalty should be added to any noise prediction.

162 If the DEFRA NAN-R-45 recommended indoor low frequency noise targets are applied in conditions for the ongoing operations of the Project for all sound sources (except for short-term construction activities) then adverse impacts from room resonance effects can be managed.

163 In consideration of the above concerns, the project target noise limits of ETSU-R-97 will not be met and the conjoined projects should not be granted approval.

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DECLARATION

175 In preparing this report I have made all the enquiries that I believe are desirable and appropriate and no matters of significance which I regard as relevant have to my knowledge been withheld.

176 William Leslie Huson

177 16 April 2023

APPENDIX (Pages 21 to 48)

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ORIGINAL PAPER

Wind Farm Noise Uncertainty: Prediction, Measurement and Compliance Assessment

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Abstract In most jurisdictions containing wind farms, base noise limits have been set by local regulatory authorities, with the intention of protecting the amenity of surrounding communities. It is a standard requirement that during the planning process for a new wind farm, the developer demonstrates that the proposed wind farm will comply with the relevant limits. At present, results from noise prediction models are commonly presented without uncertainty values, despite the fact that simplifications and approximations have been made in the models. Therefore, when prediction models indicate that the wind farm will generate noise within 3 dB of base noise limits, it is likely that these limits will be exceeded. Despite the fact that regulatory authorities often require that compliance measurements are taken to validate predictions of wind farm noise, it is very difficult to make substantial changes to noise emissions, without a corresponding reduction in electrical power output. Current methods of compliance assessment do not provide an indication of the amount of time that wind farms exceed allowable noise limits as they focus on 'average' levels only. Therefore, it is possible for wind farms to exceed allowable limits on a regular basis, and by significant margins. Hence, a more conservative approach is warranted during wind farm noise prediction and it is proposed that the upper level of the uncertainty estimate of the prediction model should not be permitted to exceed the allowable level.

Keywords Wind farm noise · Wind farm compliance · Measurement uncertainty · Propagation model uncertainty

1 Introduction

Prediction of wind farm noise levels at a receiver location involves acoustic modelling to simulate the various effects that influence noise propagation. These effects include ground reflections and absorption, the influence of terrain and man-made barriers, scattering due to vegetation and atmospheric turbulence, atmospheric absorption, meteorological conditions, reflections from vertical surfaces, large source heights and finally spherical spreading of the sound rays as they move further away from the sound source. Since the early 1970s, many propagation models of varying complexity have been developed and validated to varying degrees. The most commonly used propagation models are the CONCAWE and ISO 9613-2 models, since these models are considered adequate by many practitioners and they are the simplest to implement and are available in many software packages. Therefore, this paper will focus on these models exclusively.

Measurement of wind farm noise at a receiver location is usually carried out through unattended monitoring as this enables data collection to span several weeks, or even months, to ensure that a sufficient number of data points have been collected. Over the measurement period, significant variations in the measured noise level occur for a given hub height wind speed, mainly due to changes in local wind speed and variations in atmospheric conditions, which influence both the turbine sound power output and the attenuation due to propagation from the turbines to the residence. Therefore, it is important to measure the background noise levels that occur when the wind farm is not operating to estab-

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lish the difference between various aspects of the noise for operational and non-operational conditions. Large differences are likely to lead to increased levels of perception and annoyance.

The aim of compliance testing is to verify that a new wind farm development adheres to noise limits. This is a requirement of some regulatory authorities, and it is also a form of reassurance for members of the local community that wind farm noise emissions do not exceed predicted values. Compliance methodologies typically involve plotting the $L_{A90,10\,\mathrm{min}}$ against the wind speed at hub height and then finding the line of best fit via regression analysis. This approach results in a large number of data points exceeding the allowable limit since compliance is determined based on the position of the 'average' curve with respect to the allowable limit curve. This highlights the need for caution when interpreting data from prediction models and measurements, emphasising the importance of acknowledging uncertainties.

Both prediction models and measurements are subject to some uncertainty. Therefore, to ensure that results are meaningful and representative, it is important to provide uncertainty estimates. In the context of modelling wind farm noise propagation, multiple uncertainties arise due to the large propagation distances involved, contributions from multiple turbines, uncertainties in sound power level and the significant variations in meteorological conditions that occur over time. On the other hand, uncertainties in measured data result from uncertainties in microphone location, contamination of the noise data by wind and extraneous noise, proximity to reflective surfaces, seasonal variations in background noise and instrumentation tolerances. The large number of uncertainties involved in the prediction and measurement of wind farm noise means that exceedances of allowable limits are likely to occur, particularly at residences where borderline compliance is achieved. The most reasonable approach would be to specify that the upper level of the uncertainty estimate corresponding to the prediction model, should not be permitted to exceed the allowable level.

2 Propagation Modelling Uncertainties

As part of the planning process for new wind farm developments, it is usually a requirement to undertake predictions of the noise level for regions surrounding the wind farm. The results are generally presented in the form of a contour map, from which the predicted noise levels at relevant receivers can be ascertained. To predict the outdoor noise level at a particular residence due to a wind farm, it is necessary to know the turbine sound power level; the distance, topography and type of ground cover between the residence and each turbine; and the meteorological conditions. Wind farm noise assessment procedures generally specify that input parameters to the propagation model are conservative and therefore apply to worst-case conditions. Worst-case scenarios include downwind ($\pm 45°$) conditions, acoustically reflective or 'hard' ground and specific temperature and humidity specifications. Despite the fact that these input parameters are chosen conservatively, it is impossible to remove the uncertainties associated with the prediction model itself. These uncertainties are not always compensated by conservative inputs to the model as worst-case conditions can occur at a given residence.

The sound power level that is used as an input to propagation models also has an associated uncertainty. This is due to approximations used in the sound power measurement methodology and the variations in wind farm operational conditions, which can be significantly different from the ideal conditions that exist during sound power measurements. All noise propagation models used to predict noise at relevant receivers contain uncertainties. These arise as a result of considerable variation in ground surface properties over large distances, influences of topography and variations in atmospheric wind and temperature conditions with time and location. Thus, propagation modelling results should always be reported with an expected uncertainty value as well as a description of the conditions that have been modelled.

2.1 Uncertainty in Turbine Sound Power Level

The sound power radiated by a wind turbine is a measure of the total sound energy generated by the turbine. The sound pressure level measured with a microphone represents the strength of the sound field at the microphone location. To measure sound power accurately, it would be necessary to take at least 20 sound pressure measurements on a spherical surface around the turbine nacelle at a distance of about 200 m. As this is impractical, an approximate method has been detailed in the IEC 61400-11 Ed.3.0 [11] standard, which is widely used. The uncertainty associated with this method can be quantified using procedures outlined in IEC 61400-11 Ed.3.0 [11]. Typically, sound power measurements are undertaken by the wind turbine manufacturer under ideal conditions. Hence, the actual sound power emitted by the wind turbine installed in the field will vary depending on topography, proximity to other wind turbines, surface roughness and meteorological conditions. Currently the influence of topography and wind farm layout on wind turbine noise generation is not well understood and more research in this area is needed. Thus, the contribution of these factors to the uncertainty is difficult to quantify at present.

2.1.1 Uncertainty in Manufacturer's Sound Power Data

The procedure for determining the sound power of a wind turbine described in the IEC 61400-11 Ed.3.0 [11] standard is specific to measurements near a wind turbine. According to this method, instrumentation is positioned close enough to minimise uncertainties in propagation losses and far enough to assume plane wave propagation. The sound pressure level is measured at a single point on the ground at a distance from the turbine equal to the nacelle height plus one blade length. The measured value is used to estimate the sound power level. As aerodynamic noise is radiated from the outer part of the blades [20] and low-frequency noise is associated with blade/tower interaction, the assumption of the hub being the source centre for all frequencies is only a rough approximation and results in the measured sound power level having a significant degree of uncertainty associated with it, which is the reason that it is referred to as the 'apparent sound power.'

In addition to the uncertainty associated with the point source assumption, there is also an uncertainty associated with source directivity effects. Use of a single downwind measurement position in determining the wind turbine sound power implies that wind turbine noise is not at all directional in nature in the vertical plane and if it is directional in the horizontal plane, then the downwind measurement will represent the worst case. This may be true for low-frequency noise, but the use of the single measurement location is likely to result in an underestimate of the sound power levels in the mid- to high-frequency range due to directivity of the generated sound in the vertical plane. The IEC 61400-11 Ed.3.0 [11] standard allows for manufacturers to measure the sound pressure level at three other positions spaced horizontally at 90° intervals from the reference position and at the same distance from the wind turbine. These measurements could be used to estimate environmental noise levels for wind conditions other than directly downwind, but instances of this use are rare.

The result of only measuring at one ground location and not including directivity information in the vertical direction is that there is a level of uncertainty associated with converting the measurement to a representative sound power value. Thus any sound power data should be accompanied by uncertainty estimates. Typically, the uncertainty associated with sound power measurements is 1–2 dB(A) [14]. If standard deviation data are available, it is recommended [14] that an amount of 1.645σ (where σ is the standard deviation) should be added to the reported sound power levels. If no standard deviation data are available, an amount of 2 dB(A) should be added, which would increase the predicted sound pressure level at the receiver by the same amount.

2.1.2 Additional Uncertainties in Sound Power Associated with Operating Conditions

As mentioned previously, sound power is typically measured by the manufacturer under ideal conditions. When a wind turbine operates in a wind farm, there are a number of factors that contribute to an increase in the uncertainty associated with manufacturer's sound power data. These include topography, turbine spacing, meteorological conditions, surface roughness, turbine rotational synchronicity, and turbine operating mode. The effects of these variables on the sound power level are discussed below. Further research is needed to quantify the uncertainty associated with each variable.

The topography surrounding a wind farm can influence the angle at which wind is incident on the turbine blades. When turbines are mounted on the top of a hill, the air flow has a vertical component so the net air flow strikes the turbine blades at some angle to the horizontal. This changes the loading on the blade, hence influencing the noise generation. Undulating terrain also contributes to an increase in the atmospheric turbulence, and hence turbulent in-flow to the wind turbine blades. The result of this turbulent in-flow is a significant increase in the wind turbine sound power output. Since wind turbine sound power measurements are undertaken by manufacturers for incident air flow arriving horizontally at the turbine after propagating a considerable distance over flat ground, there is an uncertainty associated with using this data for a wind turbine located in hilly terrain.

When a wind turbine is located downwind from another wind turbine, it suffers additional in-flow turbulence as a result of the wake of the upstream turbine(s). This increased in-flow turbulence results in a change in loading on the blades and hence an increase in the generated noise [17]. Turbines that are much closer together than recommended by manufacturers often suffer from high levels of in-flow turbulence due to being in the wake of neighbouring turbines. Unfortunately, there are a number of wind farms in Australia that have turbines spaced much more closely than the recommended distance of at least four rotor diameters specified by the manufacturer Vestas in their report [28]. This exacerbates the wake-induced, in-flow turbulence to downstream turbines. One such wind farm is the Waterloo wind farm in South Australia, which is the subject of a large number of noise complaints. This wind farm has 4 turbines separated by less than 3 rotor diameters, 12 separated by just over 3 rotor diameters and another 16 separated by less than 4 rotor diameters. The wind farm is located in hilly terrain which also adds to the expected level of in-flow turbulence and noise generation. Barlas et al. [4] have demonstrated that under stable atmospheric conditions, the sound pressure level can increase by up to 7.5 dB at the wake centre. This could therefore be considered as a maximum uncertainty associated with the effects of wake in-flow.

Meteorological conditions can affect the sound power generated by a wind turbine. Since the wind speed and direction are considered as part of the IEC 61400-11 Ed.3.0 [11] methodology, these contributions are already included in the uncertainty analysis carried out by the manufacturer. On the other hand, uncertainties associated with variations in atmospheric turbulence and wind shear are not considered in that analysis. During atmospheric conditions where the turbulence exceeds that which was present when manufacturer's data were obtained, the noise radiated from the wind turbines will increase. Under conditions of high wind shear, when the speed of the wind approaching the top of the rotor disc is significantly higher than that approaching the bottom of the disc, there is potential for localised aerodynamic stall to occur at the top of the blade trajectory. Other non-uniform in-flow conditions such as yaw, topography-induced turbulence, large-scale turbulence or wake-induced turbulence from other wind turbines can also lead to localised stall with the associated increase in noise levels.

Surface roughness is an important factor when deriving hub height wind speed from measurements made at another height, as the surface roughness length, z_0, is contained in the logarithmic velocity profile expression of Eq. (1), which is used for this calculation.

$$U(h) = U_0 \left(\frac{\log_e (h/z_0)}{\log_e (h_0/z_0)} \right) \tag{1}$$

here $U(h)$ is the wind speed at hub height, h and U_0 is the wind speed at the reference height, h_0, which is 10 m for sound power measurements made according to IEC 61400-11 Ed.3.0 [11]. Therefore, if the ground surface roughness at the location where the wind turbine is installed differs from the roughness at the ideal site used to determine sound power, there can be differences between the actual turbine sound power and the sound power used for propagation modelling [24].

Regions of constructive/destructive interference occur near a wind farm and the associated locations are defined by the relative phase of the incoming sound waves, which varies with wind direction and blade rotation rate. During stable atmospheric conditions, there is an increased probability that wind turbines will rotate at similar speeds. As a result of this near synchronicity, there is a greater chance that blade pulses from different turbines will arrive at a particular location simultaneously, increasing the local sound pressure level at that particular point in time [27]. This phenomenon is not captured in standard propagation models and is therefore a source of additional uncertainty.

There are several operating modes for a given wind turbine model. When using sound power level data as input to a propagation model, it is important to ensure that the data corresponds to the mode at which maximum noise is generated by the wind turbine noise source.

2.2 Uncertainty in the CONCAWE Model

An extensive study of propagation model prediction uncertainty was done by Marsh [19] for the CONCAWE model for source/receiver separations spanning distances of 100–2000 m. The uncertainty analysis was based on comparisons between measurements and predictions for two typical industrial sites over a range of meteorological conditions. The industrial plants consisted of multiple industrial noise sources, and measurements were carried out at a number of locations to cover different distances and terrain. The measurements were taken over a period of approximately one year to ensure that a range of weather conditions occurred. The results of this study indicated that the uncertainty is dependent on the meteorological category used in the propagation modelling. For meteorological category 6, which is often modelled to simulate worst case conditions, the 95% confidence limit for the overall A-weighted noise level was found to be $\pm$ 4.5 dB.

Marsh [19] noted that uncertainty may increase in marginal cases where a small change in receiver height results in the propagation path being defined as a valley with its associated 3 dB increase in noise levels at the receiver. Further uncertainty can arise due to approximations that are used to model ground effects. The correct procedure for modelling the ground effect is to find the difference between the noise level resulting from the direct ray path and the noise level resulting from all other paths containing one or more ground reflections. This method involves calculating the spherical wave reflection coefficient which is mathematically complex. For this reason, empirical curves were developed as part of the CONCAWE model. However, use of these curves for wind farm noise predictions increases the uncertainty, since they were developed for source heights of less than 2 m and the correction factor for source heights > 2 m has not been validated for noise sources as high as wind turbines. The uncertainty varies depending on the topography between the source and receiver and this has been discussed in more detail by Evans and Cooper [10].

2.3 Uncertainty in the ISO 9613-2 Model

The ISO 9613-2 [15] documentation provides estimates of the accuracy of the predicted overall A-weighted noise level for various source and receiver heights and separation distances. Since 'accuracy' is a qualitative term [5], it is not clear whether the stated values correspond to a 95% confidence limit. The actual 95% confidence limit value may therefore be higher. For wind farm noise propagation, the most relevant value provided in the table is an accuracy of $\pm$ 3 dB, which corresponds to the largest mean source and receiver height (5 m $< h <$ 30 m) and the greatest distance between source and receiver (100 m $< h <$ 1000 m). The ISO 9613-2 [15] documentation does not provide uncertainty values for high sources such as wind turbines, and source–receiver separation distances greater than 1 km, which are typical for wind farms. It is expected that the accuracy of the model will reduce in these situations. For instance, Scholes and Parkin [23] showed that increasing the height of the source above the ground resulted in a decrease in the attenuation due to ground and meteorological effects. Evans and Cooper [10] and Bullmore et al. [7] have compared results from the ISO 9613-2 model with measurements and found good agreement between predictions and the 'average' regression curve. However, these studies do not provide any indication of the uncertainty of the prediction model based on the measurements. In both studies, results show a clear spread in data either side of the 'average' regression curve, indicating an uncertainty of at least ± 3 dB.

As mentioned in the previous section, uncertainty may increase in marginal cases where a small change in receiver height results in the propagation path being defined as a valley [13]. Further uncertainty will result from applying the ground correction method specified in ISO 9613-2 [15] in cases where terrain is not flat. While downwind propagation is assumed by the ISO model, only wind speeds between 1 and 5 m/s (measured between 3 and 11 m above the ground) are valid and significant deviations from the model may be expected for wind speeds above the 5 m/s limit [16].

3 Measurement Uncertainty

To provide an indication of measurement quality, it is imperative to carry out an uncertainty analysis. This procedure is often not mandatory in relevant guidelines and standards and therefore it is not yet routinely considered. The implications of this omission are that it is not possible to determine if sound pressure level predictions are reliable or to ascertain whether there is a possibility that compliance limits could be exceeded at sensitive receiver locations. The latter is relevant in cases where borderline compliance is achieved, particularly where complaints are involved. Determination of measurement uncertainty also facilitates comparison of results measured at different wind farms as well as comparison between background and operational data. There are several sources of uncertainty in wind farm measurements and these are outlined in the following paragraphs. Good practice, such as traceable calibration, detailed record keeping, appropriate choice of instrumentation and positioning, and careful calculation can reduce this uncertainty.

A number of variables related to microphone placement can contribute to uncertainty. These variables include the height of the microphone above the ground plane; distance to any reflective surfaces; proximity to sources of wind-induced noise such as trees and bushes; and possible inconsistencies in microphone placement for background and compliance measurements.

The presence of reflective surfaces other than the ground will result in an increase in the measured noise level at the microphone position, increasing the measurement uncertainty. Therefore, microphones should be placed as far away from reflective surfaces as possible. At close proximity to a reflective surface (i.e. 2 m), interference between the incident and reflected sound will result in an increase in level of approximately 3 dB in 1/3-octave bands above 100 Hz [21]. Therefore, the uncertainty in the overall A-weighted level can be up to 3 dB(A) due to this effect alone.

Measurement microphones should be placed as far away as possible from sources of wind-induced noise such as trees and bushes so that the measured noise levels are representative of those heard at the residence. If the measurement microphone is placed too close to trees and bushes, the measured noise levels can be dominated by local vegetation noise not representative of noise levels adjacent to the residence, thus increasing the uncertainty that the measured noise level is representative of the level experienced by a resident. In some cases, it is impossible to ensure that the microphone is located at a distance from a residence that is deemed appropriate by standards and guidelines, while also ensuring that the microphone is sufficiently far from foliage.

To minimise uncertainty, it is important to ensure consistency in the placement of the measurement microphone for background and compliance measurements. Any inconsistencies can lead to unrealistic results such as background levels that are higher than operational levels. This could occur if background measurements were made close to foliage, but compliance measurements were made in an open area. Since background levels often influence allowable wind farm noise limits, it is crucial to measure in the same location for background and compliance measurements.

The calibrator used to check that the microphone is performing adequately also has an associated error and this will affect the accuracy of the data measured by the microphone. This error is usually ± 0.2 dB for Class 1 calibrators and for other calibrators it is not greater than ± 0.5 dB. Another point to consider is that the tolerance ranges on Type 1 sound level meters at low frequencies are high when using A-, C- and Z-weightings. This could result in measurement errors as well as variations in the noise levels measured with different instrumentation, particularly where the measured signal is dominated by low-frequency noise. Other sources of uncertainty related to instrumentation are listed in Table 1, which was adapted from IEC 61672-1 [12]. This table lists the maximum expanded uncertainty, which corresponds to a level of confidence of approximately 95 %. The sources of error listed in Table 1 are relevant for noise measured at frequencies less than 1000 Hz since the wind farm noise spectrum at a typical residence located more than 1 km from a wind farm will be dominated by these frequencies.

To determine the overall expanded uncertainty, U_t, associated with instrumentation, the individual uncertainties, U_i, are combined as follows:

Table 1 Summary of some of the relevant sources of error for noise measured at frequencies < 1000 Hz

Source of error	Maximum expanded uncertainty (dB)
Calibrator	± 0.2
Directional response > 250 Hz	± 0.3
Frequency weightings A, C, Z, unweighted (< 200 Hz)	± 0.5
Frequency weightings A, C, Z, unweighted (≥ 200 Hz)	± 0.4
Level linearity error	± 0.3
1–10 dB change in level between measurement and calibration	± 0.3
Electrical output	± 0.1
Static pressure influence	± 0.3
Air temperature influence	± 0.3
Humidity influence	± 0.3

Values are provided by IEC 61400-11 Ed.3.0 [11]

$$U_t = \sqrt{\sum_{i=1}^{n} (U_i)^2} \tag{2}$$

The resulting uncertainty due to instrumentation is approximately 1 dB.

4 Compliance Assessment Procedures

The aim of compliance testing is to verify that a new wind farm development adheres to allowable noise limits. Typically, allowable limits are specified in terms of a baseline L_{A90} value or background L_{A90} + 5 dB(A), whichever is greater. A typical compliance plot is shown in Fig. 1. The red curve in this plot shows the allowable limit, which is determined with reference to the background regression curve shown in green. It can be seen that the allowable limit is significantly higher than 40 dB(A) at hub height wind speeds above 12 m/s. Each data point in the plot was measured during operational conditions and represents a 10-min average of the L_{A90}, which is the noise level exceeding 10% of the time. The L_{A90} is plotted against the wind speed at hub height and a regression curve, such as the blue curve in Fig. 1, is fitted to the data. There are a number of issues with this approach and these will be discussed below.

The $L_{\text{Aeq},10}$ and $L_{A90,10}$ quantities are not equivalent for measurements of wind farm noise. The assumption that wind turbine noise does not vary rapidly with time is inconsistent with extensive literature on the subject [6,18,25]. Wind farm noise can be significantly underestimated by $L_{A90,10\,\text{min}}$ levels as peaks that are associated with unsteady effects such as amplitude modulation are not present for 90% of the time and hence their disturbance potential is never evaluated. In other words, a wind farm could be making excessive noise of a disturbing character for 9 out of every 10 min but the noise would be characterised based on the quietest 1 min. According to ETSU [9], the $L_{\text{Aeq},10}$ is at least 1.5–2.5 dB(A) higher than the $L_{A90,10}$ for wind farm noise and this is not taken into account in current compliance methodologies such as the SA EPA guidelines [22]. This is despite the fact that the Australian standard, AS 4959 [1] states that a minimum of 1.5 dB(A) should be added to the $L_{A90,10}$ to account for the difference between the $L_{Aeq,10}$ and $L_{A90,10}$ quantities.

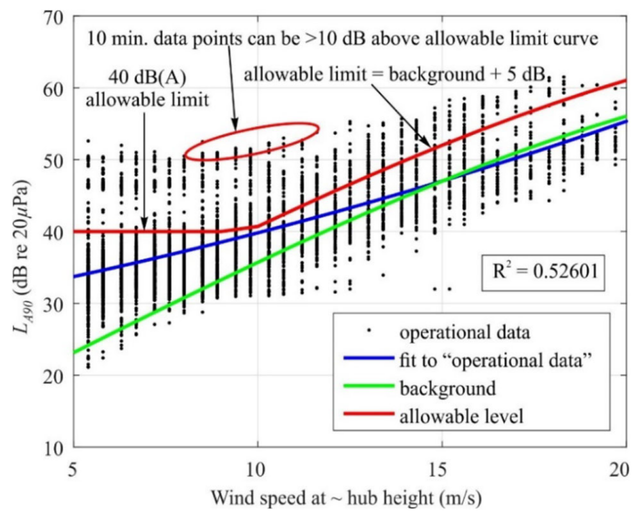

Fig. 1 Comparison of data regression curve (blue) to allowable limits based on the larger of 40 dB(A) and background + 5 dB(A). This wind farm would be considered compliant despite the fact that many data points are more than 10 dB(A) above the allowable values

The 'average' noise level as defined by the regression curve does not necessarily represent the level of wind turbine noise. In fact, in the worst-case scenario, where the wind farm noise regression curve was the same as the allowable limit curve, the wind farm would be allowed to exceed the allowable limit for 50% of the time. In any case, a compliant wind farm can generate noise levels significantly higher than the allowable limit for a substantial percentage of time. In

Fig. 1, the noise levels measured during wind farm operation exceed the allowable limit more than 30% of the time.

The noise level measured during operational conditions represents wind farm noise plus background noise, whereas the quantity of interest is wind farm noise only. The uncertainty associated with this issue can be minimised by plotting data between the hours of 11pm and 5am when there is high wind shear so that the turbines are rotating and producing more than 70% of their rated power, while the wind speed at the residence where compliance testing is being done is less than 2 m/s. This approach maximises the signal-to-noise ratio between wind farm noise and background noise. An alternative approach is to take measurements with and without the wind farm operating for the same weather conditions at a similar point in time. The determination of the wind farm only contribution to the noise levels when the wind farm is operating may be determined using one or both of the following methods, although the second method may be a bit complex to include in a regulation.

1. Downwind conditions (± 45°) only should be considered for this analysis and data contaminated by extraneous noise and periods of rainfall should be discarded. After dividing noise level data into night-time (11pm–5am) and the remainder (5am–11pm) and further dividing into turbine OFF and turbine ON levels, data should be plotted as a function of wind speed at hub height and a curve of best fit plotted through the data points for the night-time data and then separately for the remaining (daytime and evening) data. To obtain the wind farm contribution, the level with the turbines OFF should be subtracted logarithmically from the level with the turbines ON. For increased accuracy, the night-time data can be further sub-divided into low and high wind shear conditions.
2. Alternatively, the data in each grouping just described can be presented as a probability density function plot as described by [2,3]. This method calculates the probability of the existence of a particular dB(A) level that is due only to turbine operation. Its advantage for compliance checking is that it allows regulations to be set along the lines of 'wind farm noise levels should not exceed *x* dB(A) for more than 10% of the time'. It also allows the percentage of time that a wind farm is non-compliant to be determined.

Although wind farm noise at a residence is generally well correlated with the combination of wind speed and direction at hub height, background noise levels are not. This is due to the variation in atmospheric conditions over time, which results in differences in vertical wind shear as well as directional shear [27]. The variation in wind speed and direction is not only a function of height, but also of location, due to influences of the surrounding topography. For example, a residence that is located in the vicinity of a wind farm situated on a ridge-top can experience lower wind speeds in the downwind direction compared to the upwind direction, due to being located in the lee of a hill for the former case [8]. In conditions where there is a large difference between wind farm noise and ambient noise, it is inappropriate to increase the allowable limit to 5 dBA above the regression curve of background noise versus hub height wind speed, although this is recommended in various wind farm noise planning guidelines. Since conditions of low wind speed at a residence corresponding to relatively high wind speed at hub height often occur during the night-time when the atmosphere is stable, it is possible that residents will suffer sleep disturbance, even if the wind farm is in compliance.

Background noise levels are subject to change on a seasonal basis due to changes in farming activity, vegetation, surf size and river flow, etc. Therefore, the background regression curve may not be representative of all times of year. During seasons when the background noise levels are relatively low, wind farm noise could be substantially higher than ambient levels. This is likely to result in disruption of amenity for people living in areas near wind farms that are subject to these effects.

5 Discussion and Conclusions

The accuracy of noise propagation modelling is often the subject of discussions in court, especially when predicted noise levels are close to allowable noise levels. Generally most noise models allow noise predictions to be made for the worst-case meteorological conditions that are expected to occur on a regular basis. However, the best accuracy that can realistically be expected for noise level predictions at distances of 1 km or more from a wind farm is ± 3 dB, although ± 4 dB is probably more realistic when uncertainties in the turbine sound power levels are taken into account. Some practitioners claim an accuracy of better than ± 2 dB but there is insufficient data available to confirm this. The difficulty in obtaining accurate predictions is mainly associated with the variability of the atmospheric wind and temperature profiles over time and geographic location. An example of the inaccuracy of the ISO9613-2 prediction method is provided by Stigwood et al. [26] for the Cotton Wind Farm. In their Fig. 1, Stigwood et al. [26] show that predictions are consistently 2–4 dB below the average of the measured $L_{A90,10}$ data over a range of wind speeds in the downwind direction. The difference between the decibel level exceeded 10% of the time and the predictions is even greater (by about a factor of 2).

Measurement uncertainty can be minimised provided good practices are followed, such as traceable calibration, detailed record keeping, appropriate choice of instrumentation and positioning, and careful calculation. The large variations in noise level as a function of hub height wind speed that are observed during long-term measurements of wind farm noise are not caused by measurement uncertainty in most instances. These variations are mainly caused by changes in meteorological conditions, which affect sound power output and noise propagation, as well as background noise levels.

Background noise levels are typically measured prior to wind farm operation and it is commonly assumed that the representative background level is defined by the 'average' regression fit to the data. However, there seems to be no justification for this approach, particularly as local background levels are not necessarily correlated with hub height wind speeds. A more conservative approach would be to consider the 90th percentile value of the background $L_{A90,10}$ for each hub height wind speed as the representative value. Even better, background noise levels should not be used at all in setting allowable limits, as allowing the wind farm noise level to exceed the mean L_{A90} by 5 dBA will result in many extended time periods when the wind farm noise will exceed the background noise by much more than this, especially at night.

The $L_{\mathrm{Aeq},10\,\mathrm{min}}$ and $L_{A90,10\,\mathrm{min}}$ quantities are not equivalent for measurements of wind farm noise and it is well known that these quantities differ by at least 1.5–2.5 dB(A) [1,9]. This is not taken into account in current compliance procedures [22], which means that a marginally compliant wind farm may actually be non-compliant. Moreover, the $L_{A90,10\,\mathrm{min}}$ is a poor descriptor of wind farm noise, which is known to vary significantly in level with time.

There also seems to be a lack of justification for assuming that the 'average' regression fit to data measured during wind farm operation is representative of wind farm noise. Since there are so many data points that exceed this curve, the wind farm could exceed allowable limits on a regular basis at any time during the day or night. A more reasonable approach would be to specify percentages of time that the wind farm could exceed various noise levels at different times of the day. For example, during the night-time, wind farm noise must not exceed X dB(A) for Y% of the time, XX dB(A) for YY% of the time, etc.

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Problems related to the use of the existing noise measurement standards when predicting noise from wind turbines and wind farms.

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Overview

- Noise Measurements (IEC 61400-11:2002)
  - Short description of the measurement method
  - Use of measurement results, including influence on inaccuracy.
- Noise prediction
  - Terrain and meteorology influence on the actual emitted sound
  - Methods used in noise calculations
- Noise assessment
  - Descriptors
  - Noise limits
  - Further investigations needed

Noise Measurements (IEC 61400-11:2002)

We correct for:

Air pressure
Air temperature

Standard terrain roughness z = 0.05 m

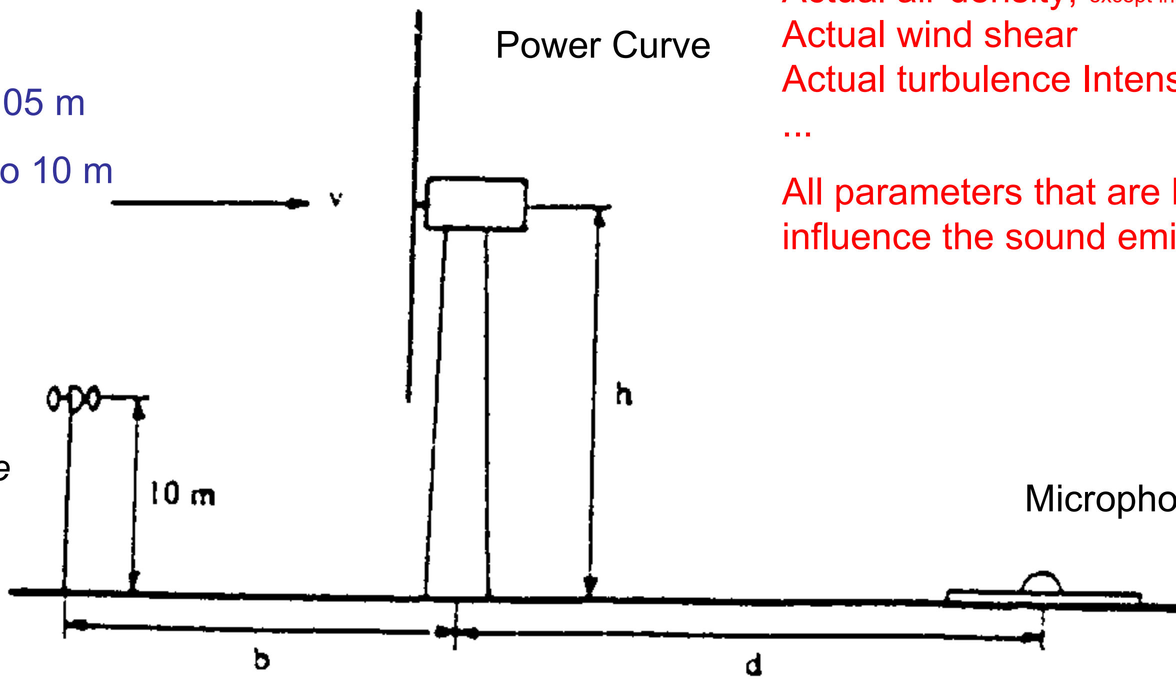
All recalculated to 10 m wind speed

We do not correct for

Actual inflow angels
Actual air density, except in the power curve
Actual wind shear
Actual turbulence Intensity
...

All parameters that are known to influence the sound emission

Anemometer
For background noise only



Noise Measurement

- The results are standardized noise levels, which are fairly comparable from measurement to measurement on a given turbine type.
- The wind turbine is used as a wind speed meter through a power curve measured on an ideal site (IEC 61400-12) OBS impossible if actual terrain does not fulfill conditions
- Other parameters influence the noise level: relative humidity, turbulence, inflow angle, wind shear, turbine pitching are not accounted for.

- The result is a fairly good tool for verification of warranties, but not a good tool for predicting noise at imission points where people actually can get annoyed.

- The Sound Power Level related to the produced power or at least the sound power level as a function of hub height wind speed could be a more basic relationship

Typical problems in using the measurement results

- Where do we see the major deviations from standardized conditions during actual use of measurement results

- The wind turbines are almost always raised at sites where roughness differ from the standardized completely flat measurement site.

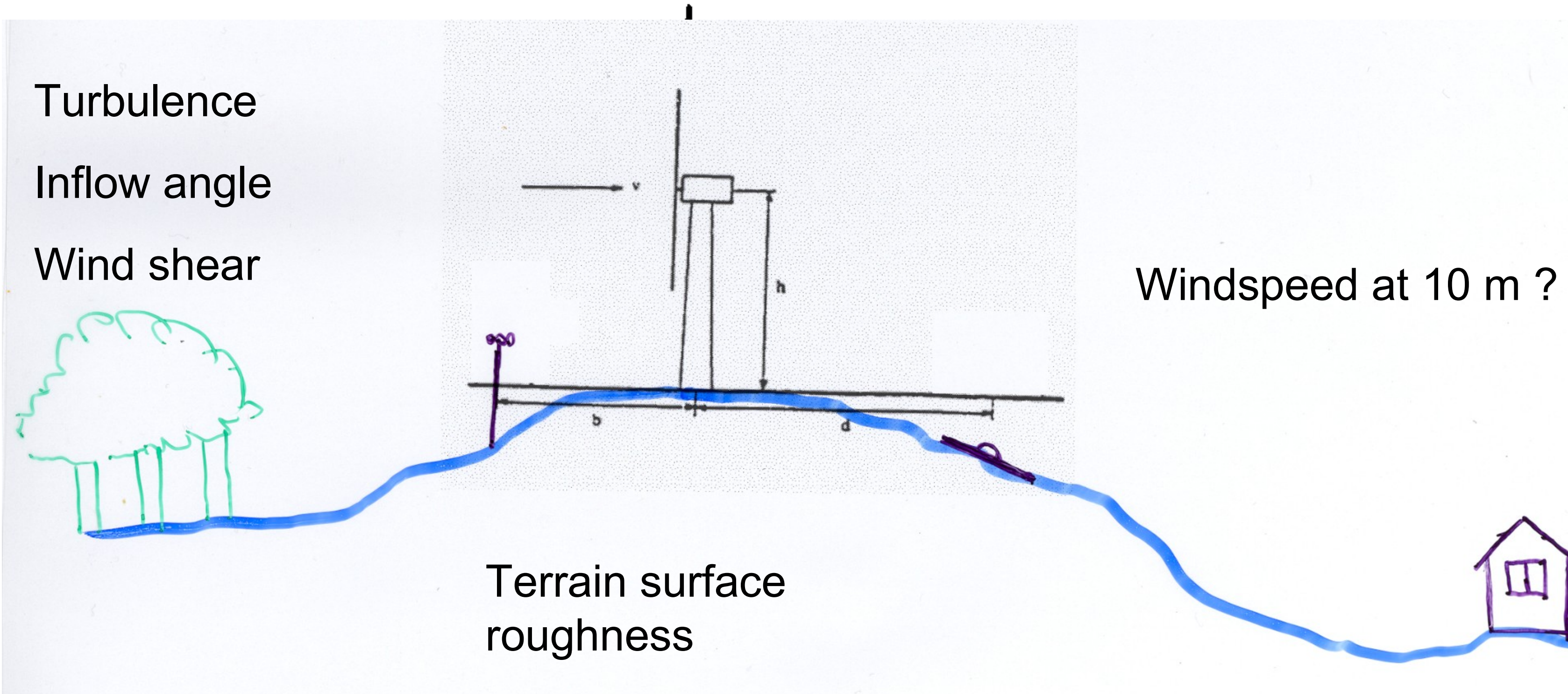
- Further we see different air density
- different wind shear
- different turbulence in inflow air
- different inflow angles

- Finally we often see other hub heights than used during documentation

Use of measurement results

For noise control measurements

For noise level calculations



Conclusion on measurement results

- The differences in site conditions creates differences in emitted sound power level.
- The differences could be both increased and decreased emitted sound power levels in real life applications
- The differences will transfer directly to the imitted sound power levels, and may thereby create increased annoyances in real life

- Therefore – site specific sound power levels should be used unless a good safety margin is present using standardized emission levels.

Uncertainty

- According to IEC 61400-11:2002 the standard deviation of a measurement results is app. 0.9 – 1.5 for an ideal site
- If the measurements are made at a site with considerable turbulence intensity or wind shear the standard deviation can be app. 2.0 dB
- The result is that when used for calculating the noise from a wind farm at an imission point, some WTG will be higher than the expected level and some will be lower.
- To correct for this, the measured inaccuracy <u>cannot</u> be placed upon the total calculated level, but must be included in the calculations.
- The result is that the higher the number of WTG's in the project is, the smaller the resulting inaccuracy.
- If the results are used for calculating the noise from a wind farm the standard deviation should be calculated as the weighted standard deviation

$$\sigma_{res} = \sigma_{method} + \sigma_{source} = \sigma_{method} + \frac{\sqrt{\sum(\sigma_i \cdot 10^{L_i/10})^2}}{\sum 10^{L_i/10}}$$

Solution to the outlined problems

- Accept that different sound power levels should be used in predictions and warranties.
- Avoid using sound power levels that include inaccuracy in predictions unless there is a good safety margin.
- The inaccuracy should be included in the calculation – the higher the number of WTG's the less the probability that all are in the high end of the uncertainty interval
- Use sound power levels that at least are corrected for: hub height, wind shear, air density, turbulence, inflow angle
- Be careful to make sure that the background noise measurements and wind conditions at the turbine positions uses the same reference position.

Noise level calculation models

- There are lots of different noise level calculation models:
  - ISO 9613-2 which is the model that we see the most
  - VDI 2714
  - Concawe
  - BS 5228
  - General Prediction Method (Danish)
  - Danish EPA Guidelines
  - Netherlands Guidelines 1999
  - Swedish method (land/sea)
  - .....

- Most of the methods are developed for noise from Industry, wind speeds below 5 m/s and standard meteorological conditions and must be suspected to give poor results at larger distances.
- ISO 9613-2 is known sometimes to overestimate the terrain effects if soft ground is used
- Manufacturers, developers, consultants and authorities have an interest in a noise level calculation model developed specifically for wind turbine noise

Noise calculation models

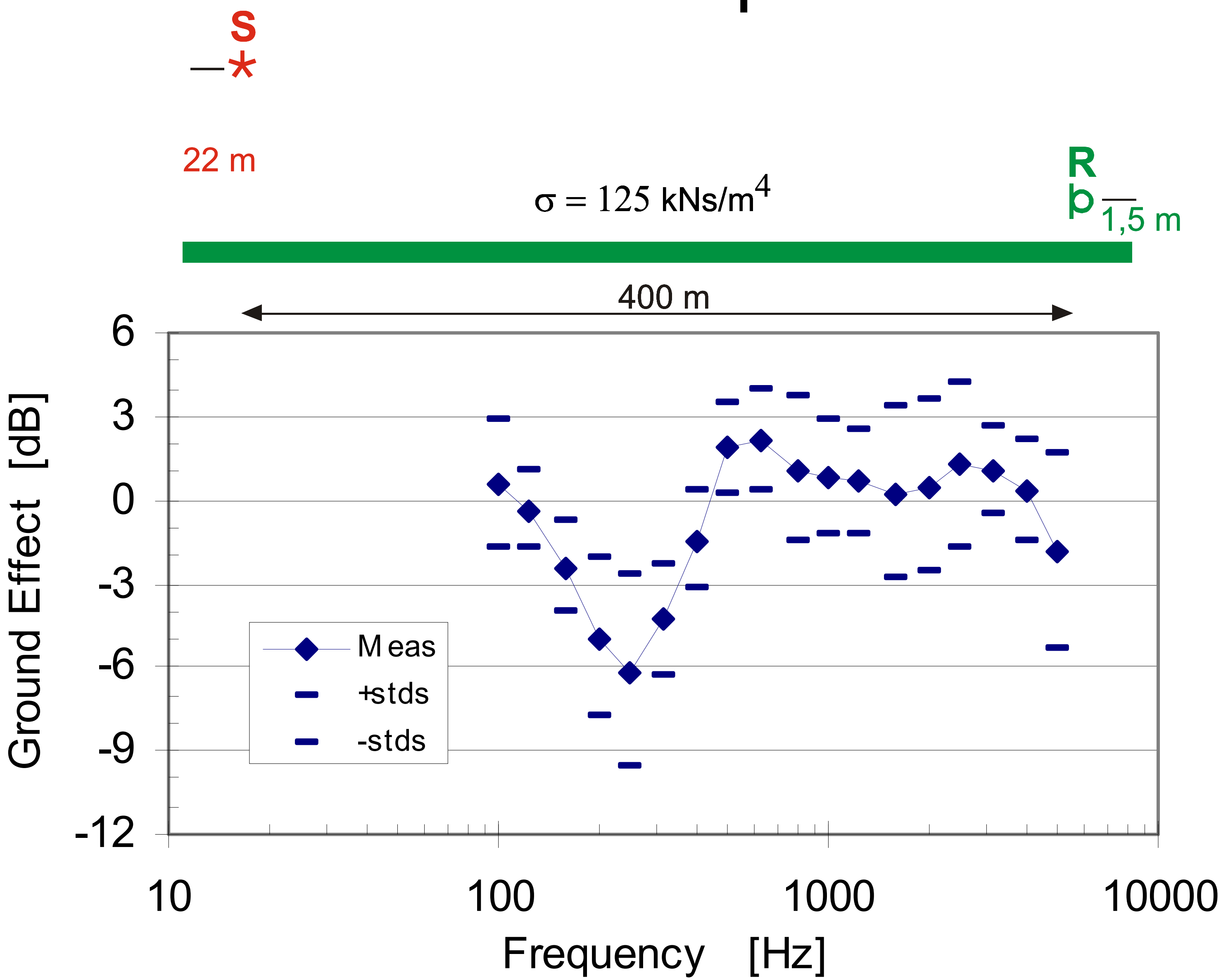
- In an EU project JOR3-CT95-0065 a model for wind turbine noise propagation (WiTuProp) was developed giving good results

- The WiTuProp model takes into account
  - meteorological conditions:
    - Wind speed / terrrain surface roughness and direction
    - Air temperature and air temperature gradient
    - Relative air humidity

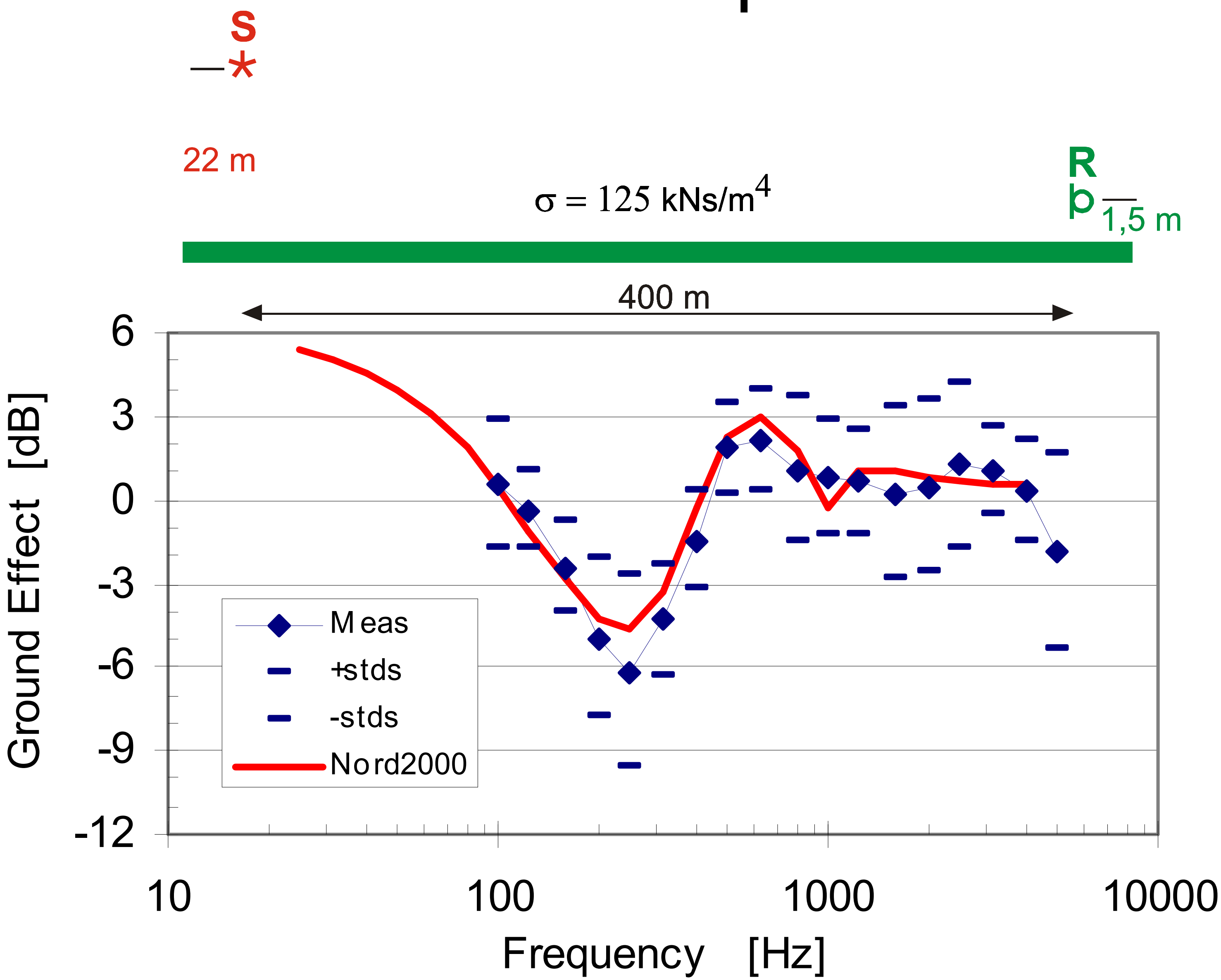
  - The ground type
    - Flow resistivity for grassland and harder surfaces
  - Screening (by terain or screens / barriers)

- WiTuProp is a special case of a more comprehensive model developed later: *NORD2000*

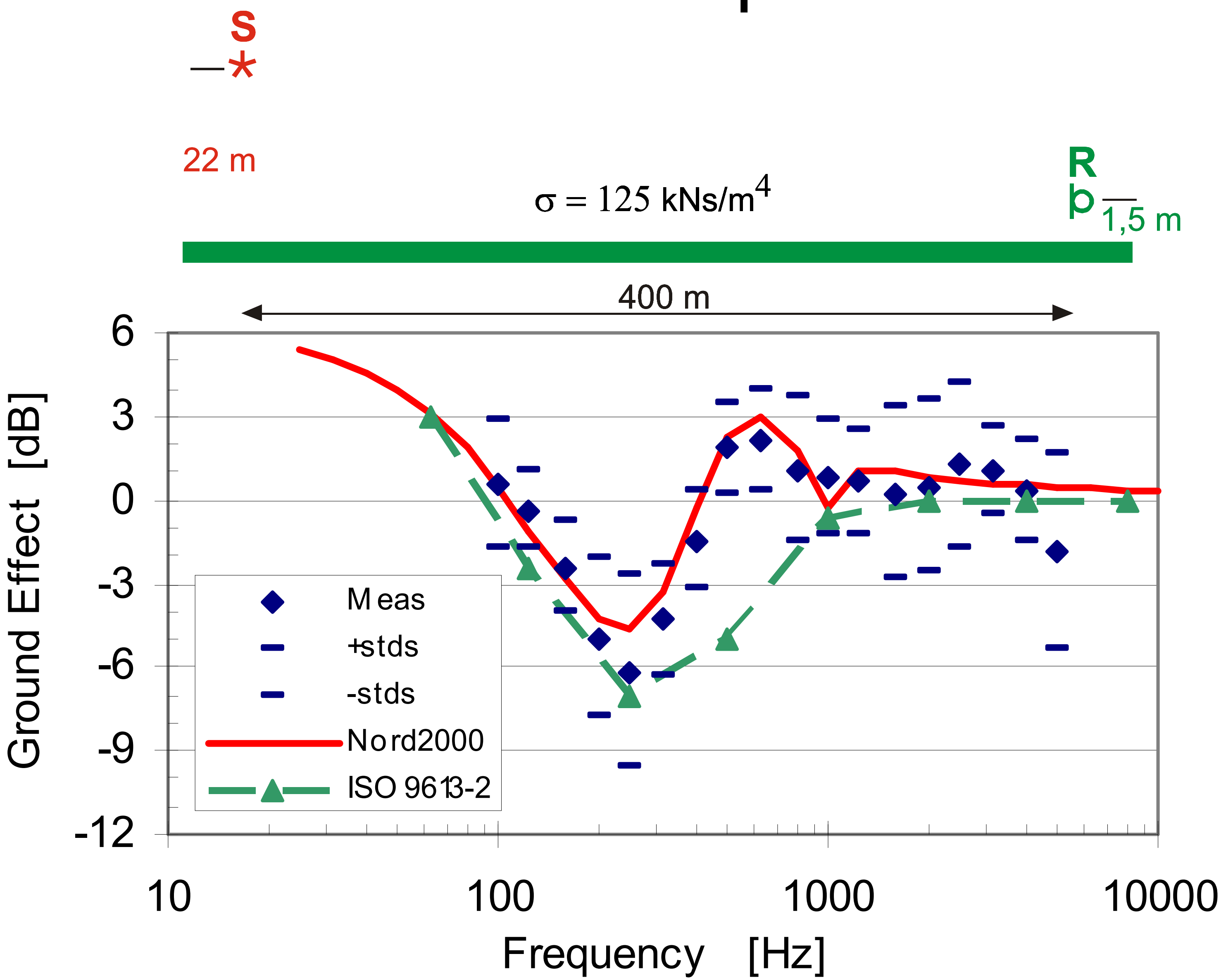
Nord2000 / WiTuProp vs. ISO 9613-2



Nord2000 / WiTuProp vs. ISO 9613-2



Nord2000 / WiTuProp vs. ISO 9613-2



Nord2000 model

- Meteorological conditions are better covered
- Complex terrain profiles (hill/valley)
- Mixed ground
- Terrain roughness
- Improved screen modelling
- 1/3 octave-band results
- Physical model – NOT empirical

Recommendation if the advanced model is not used:

- Use ISO 9613-2
- Make sure that hard terrain is used
- Be careful when defining screening effects from terrain - specially edge effects can be difficult to model

Noise Assessment

- The noise level at the imission points are normally given as an A-weighted noise level at different wind speeds.
- A tonality evaluation is normally included for the receiving points.

What do we know of the annoyance of the noise:

- We know that noise from wind turbines sometimes annoys people even if the noise is below the noise limits.
- Often people complaints on low frequency noise which many investigations often show in not present
- The noise limits are usually adapted from industrial noise limits and are based upon the principle that a given percentage of the population will feel annoyed when the limit is exactly fulfilled.
- Evaluation of tonality in the turbine noise is more based on the reproducibility of the results than on pure knowledge on what is actually annoying

Noise assessment

- Other descriptors need to be investigated to understand the annoyance caused by wind turbines
  - Low frequency noise and Infrasound – we cannot see it in our measurements
  - Modulation – may be the parameter that is heard as low frequency noise
  - Masking – which noise can mask noise from wind turbines
  - Other characteristics
  - ..
- This mean that tape recordings should me made on all sites in order to enable later analysis of up till now unrecognized parameters.
- In order to enable listener tests, artificial head investigations should be made
- We as a producer cannot cover this alone, since the local rules always need to be followed

Our recommended research program

- Artificial head measurements on real turbines of different sizes
- Background noise measurements on real sites
- Listener tests on obtained results
- These measurements are being made on a test basis during our Danish measurements

- General Research that is needed in this area includes
  - Psychoacoustic experiments
  - Listener test
  - Measurements at low frequencies
  - Analysis for other characteristics
  - ..

Questions ?