Report

PSO-07 F&U project no 7389
Noise and energy optimization of wind farms

Validation of the Nord2000 propagation model for use on wind turbine noise

Performed for Energinet.dk

AV 1236/09

Project no.: A580521

Page 1 of 70 incl.
4 annexes

8 October 2009

DELTA
Venlighedsvej 4
2970 Hørsholm
Denmark

Tel. +45 72 19 40 00
Fax +45 72 19 40 01
www.delta.dk
VAT No. 12275110

Title
PSO-07 F&U project no 7389
Noise and energy optimization of wind farms
Validation of the Nord2000 propagation model for use on wind turbine noise

Journal no.	Project no.	Our ref.
AV 1236/09	A580521	BSG-BP-KDM/ilk

Client
Energinet.dk
Tonne Kjærsvej 65
7000 Fredericia

Client ref.
Contract no.: 2007-1-7389

Preface

The work presented in this report is part of the PSO-07 project “Noise and Energi optimization of wind farms” and deals with validation of the Nord2000 prediction model for wind turbine applications. The project is publicly funded by Energinet.dk under contract number 2007-1-7389. Supplementary funding to the project is given by DONG Energy, Statkraft Development, Vattenfall AB Vindkraft, E.ON Vind Sverige AB, Suzlon Energy and Gamesa.

The project has been carried out in cooperation between DELTA, DONG Energy and EMD International.

The main topics in the present report are:

- Validation of Nord2000 through loudspeaker noise measurements
- Validation of Nord2000 through wind turbine noise measurements
- Validation of Nord2000 through wind farm noise measurements

DELTA, 8 October 2009

Bo Søndergaard
Acoustics

Birger Plovsing
Acoustics

Contents

1. Summary

Combining noise and energy optimization in a tool for design of wind farms like WindPRO is only possible if the noise prediction model is able to include effects of meteorology and complex terrain situations in prediction of the noise. Nord2000 is on such prediction model. The Nord2000 model is already accepted for prediction of traffic noise and train noise in the Nordic countries.

In this report the investigations made to validate Nord2000 for elevated sources like wind turbines are described and conclusion on the validation is included.

Three stages of field validation were planned from the beginning: loudspeaker tests, single wind turbine tests and a wind farm test. The loudspeaker test is considered most important because it is possible to realize well defined situations.

Generally the conclusion is that for the tested situations Nord2000 shows a fine agreement with noise measurements for simple flat terrain with simple meteorology and for complex terrain with complex meteorology. When compared to ISO 9613-2 the Nord2000 model is an improvement especially for the complex situations.

2. Summary in Danish

Optimering af vindmølleparker både med hensyn til støj og energiproduktion er kun muligt, hvis det er muligt at inkludere virkningen af meteorologi og af komplekst terræn i støjberegningen. Dette er muligt med Nord2000-modellen. Nord2000-modellen er allerede indført som beregningsmodel for trafik- og togstøj i de nordiske lande.

I denne rapport er målekampagnerne, der er udført med henblik på at validere Nord2000 for højt placerede støjkilder som vindmøller, beskrevet, og konklusionerne på valideringen er anført.

Valideringen er udført som feltforsøg i 3 trin: Højttalerforsøg, vindmølleforsøg og et enkelt vindmølleparkforsøg. Højttalerforsøgene er vurderet som de vigtigste, da det i disse forsøg er muligt at realisere meget veldefinerede opstillinger.

Generelt kan det siges for de testede situationer, at Nord2000 viser fin overensstemmelse med støjmålingerne både for simpelt, fladt terræn med simpel meteorologi og for komplekst terræn og kompleks meteorologi. Når der sammenlignes med ISO 9613-2, kan man se, at Nord2000-modellen er en forbedring især for de komplekse situationer.

3. Aim

The aim of this part of the project is to validate the Nord2000 prediction model for wind turbine noise.

The report “Nord2000. Validation of the Propagation Model” [1] sums up validation for Nord2000 for low-altitude sources at distances of up to approx. 1000 m. For that reason the validation for elevated sources like wind turbines is considered to be a supplement to existing validation rather than a full validation.

The validation is done through a series of measurement campaigns using loudspeakers, individual wind turbines and wind farms as the source of noise.

More information on the Nord2000 method can be found in [2], [3] and [4].

4. Validation method

Three stages of validation were planned from the beginning: loudspeaker tests, single wind turbine tests and a wind farm test.

The loudspeaker tests are considered most important as the noise source is well defined in position and in strength. As the aim of the project has been to introduce the Nord2000 in wind turbine noise prediction, tests using a wind turbine as a source were planned as well. In this case the source is less well defined in both positions and in strength, and the results were expected to have a higher uncertainty. It is considered important to show that wind farm noise predictions with Nord2000 are reliable and a limited test with noise measurements and predictions for a wind farm has been included. The accuracy of this test was expected to be less than for the other 2 stages of validation.

The principle used for the validation is to determine the excess propagation effect defined as the sound pressure level relative to the free field level.

The free field noise only includes the spherical spreading of the noise, while the excess propagation effect comprises the ground and screening effect and the air absorption. The effect of vegetation has not been considered in this investigation. An example of excess propagation effect is shown in Figure 1.The figure shows the effect of pressure doubling due to the ground reflection at low frequencies giving an excess propagation effect of approximately +6 dB. At high frequencies the influence of increasing air absorption on the propagation effect is seen. In the mid-frequency range the effect of destructive and constructive interferences from the ground reflection are most often seen giving minima (dips) and maxima (peaks), respectively.

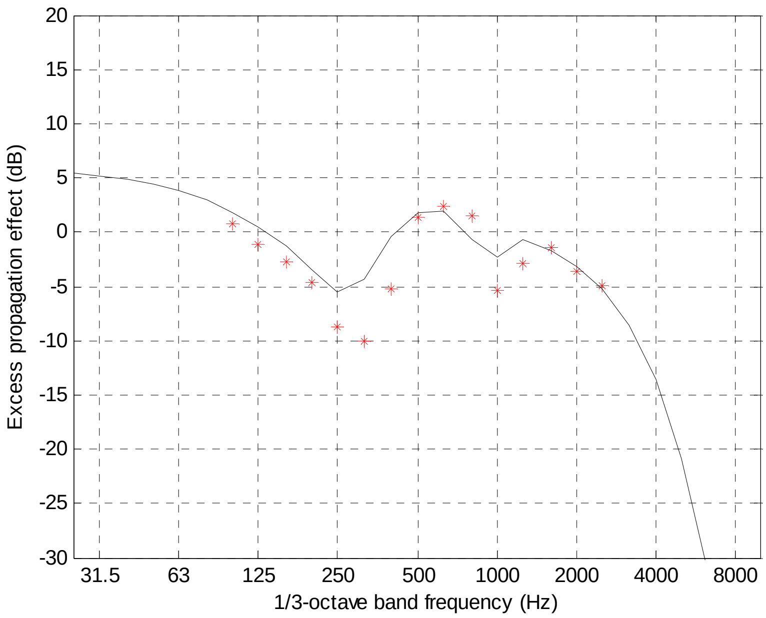

Figure 1
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 500 m, source height 30 m and receiver height 2 m.

4.1 Loudspeaker noise measurements

First a small parametric study on the influence of different variables on the noise propagation was made [6]. The purpose was to design a measurement setup, which with the least effort would give most information on the propagation. (Excess Propagation Effect).

The results of the study were that the important meteorological parameters from the propagation models are the wind speed and wind speed gradient, the temperature and temperature gradient and the wind direction. The measurements should include varying conditions for these parameters if possible. It was also found that the sensitivity to source and receiver heights are strong and it was decided to use 2 microphones at each position with different heights.

The following test setup was considered:

- Measurements in flat/simple surroundings with good possibilities for monitoring the meteorological parameters. At least 1 site.
- Same type of terrain on all sides allowing for measurements up/cross/downwind on the same day.

- Measurement distances 1 m (reference measurement at the loudspeaker), 500 m, 1000 m and 1500 m. Possibly at 2 heights (2 m and 5 m).
- Sound power level of loudspeaker system L_W 130-140 dB.
- Frequency range of interest 50 Hz - 2 kHz (air absorption reduces higher frequencies).
- Noise on/off at fixed intervals (60s). Different noise signals are emitted in a loop with 20 s breaks in between. A broad band (pseudorandom) signal band limited 50Hz - 2 kHz, and 5 broad band (pseudorandom) signals in the octave bands from 63 Hz - 2 kHz.
- Synchronizing of measurement stations.
- Measurement microphones supplied with secondary wind shields (calibrated).
- Variation in wind speed range 4 - 10 m/s.
- Variation in temperature gradient (cloud cover at least 0/8 - 6/8).
- Turbulence strength measured through anemometer.

As the measurements were field measurements and the setup of the measurements was extensive, it was not possible to fulfil these requirements entirely and small changes were decided during the measurements.

4.2 Wind turbine noise measurements

As most of the noise source data for wind turbines are from measurements according to IEC 61400-11 [7], the wind turbine noise measurements should represent this situation. The basic setup is the same as for the loudspeaker measurements but the reference measurement is on a 1.2 m circular board of 18 mm plywood on the ground according to IEC 61400-11. The rest of the measurement setup should follow the principles of the loudspeaker measurements. Measurements in up- and downwind should be made to illustrate the difference in propagation. It was hoped that these measurements could also be used to evaluate whether wind turbines can be described by a point source or it is better with a source distributed across the rotor plane.

4.3 Wind Farm noise measurements

The last part of the validation has been made through a comparison of noise measurements and predictions for a large wind farm for a single meteorological situation.

5. Measurement campaigns

The loudspeaker measurements were made on 2 locations: In flat terrain at Høvsøre in Denmark and in complex terrain at Hitra in Norway. Wind turbine noise measurements were made at Hitra.

5.1 Loudspeaker noise measurements

The loudspeaker measurement campaigns are expected to be most important and give the best results for the validation. For that reason the first measurement campaign was planned to the Risø test site for large wind turbines at Høvsøre in Denmark. At the test site a large number of meteorological parameters were measured at different heights giving a good description of the meteorological situation.

As the weather variation was small and the only significant variation was the wind direction, it was decided to repeat the loudspeaker measurements in complex terrain in connection with the wind turbine noise campaign.

5.1.1 Instrumentation

The loudspeaker system used was a Cerwin - Vega G212 with 2 12” units in parallel and a 2-channel Yamaha Professional Series Natural Sound Power Amplifier model P 2200. The noise generator was based on National Instruments Labview software and executed on a Lenovo T60 laptop with the built-in soundcard and programmed to give a cycle of signals as shown in Table 1. The noise level of the source was measured at a distance of approximately 1 m in front of the loudspeaker and registered with the measurement software NoiseLAB developed by DELTA. The noise was measured with either G.R.A.S. 40AE microphones and 26CA preamplifiers or B&K 4189 microphones, 2639 preamplifiers and a 2658 preamplifier. The noise signals were recorded on hard disc recorders type 744T and 788T from Sound Devices. All microphones were fitted with a secondary wind screen as seen in Figure 4 and Figure 9. The insertion loss of the wind screens are measured by DELTA in an anechoic chamber at Aalborg University.

Photos of the measurement setup are shown in Figure 3 and Figure 4

Signal no.	Signal type	Frequency range	Time [s]	Measured Sound Power Level [dB re 1pW]
1	Broadband (pseudorandom)	6 1/1-octaves from 63 Hz to 2kHz	50	124
2	Pause	-	10	-
3	Broadband (pseudorandom)	63 Hz 1/1-octave	50	114
4	Pause	-	10	-
5	Broadband (pseudorandom)	125 Hz 1/1-octave	50	121
6	Pause	-	10	-
7	Broadband (pseudorandom)	250 Hz 1/1-octave	50	121
8	Pause	-	10	-
9	Broadband (pseudorandom)	500 Hz 1/1-octave	50	124
10	Pause	-	10	-
11	Broadband (pseudorandom)	1 kHz 1/1-octave	50	124
12	Pause	-	10	-
13	Broadband (pseudorandom)	2 kHz 1/1-octave	50	126
14	Pause	-	20	-

Table 1
Signal cycle for loudspeaker measurements.

5.1.2 Høvsøre

It was intended to mount the loudspeaker on top of one of the wind turbines at the site, but the measurements were delayed several times for security reasons as the wind speed was too high to work outside the nacelle. It was decided to use a crane to raise the loudspeaker to a sufficient height to represent a wind turbine. The crane could only raise the loudspeaker to 50 m, but gave the opportunity to vary the source height and a height of 30 m was used as well. Heights of 50 m and 30 m are well above the valid range for the ISO 9613-2 model.

The measurements were made at 2 m and 5 m above the ground surface at three distances during upwind and downwind as shown in Table 2. When changing from downwind to upwind measurements the crane was moved from the north end of the site to the south end of the site as shown in Figure 2 and microphone positions changed accordingly.

Figure 2
Høvsøre test site. The loudspeaker position was changed between downwind and upwind measurements. The terrain is flat and typically agricultural. The indicators marked S are source positions and M are receivers. "medvind" means downwind and "modvind" is upwind.

Figure 3
The noise generator and the noiseLAB recorder were running on the same laptop. The noise generator is top left on the computer display and the recorder bottom left. The "stripchart" on the recorder shows the sequence with noise on and noise off. The amplifier is seen under the laptop.

Figure 4
Mounting of the loudspeaker and the microphone in front of the loudspeaker for the Høvsøre measurements. The elevation of the loudspeaker was 50 m and 30 m during measurements.

Microphone position	Exact distance (m)	
	Downwind	Upwind
1	456	416
2	1020	912
3	1405	1284

Table 2
Exact horizontal distances between loudspeaker and microphone for each microphone position.

During the measurements meteorological data was recorded by Risø every 10 seconds for the entire measurement period. From these data the wind speed and temperature at different heights from 2 m to 100 m and the relative humidity at 2 m height used. Of the meteorological data recorded by Risø the parameters shown in Table 3 were used. The meteorological measurements and the noise measurements were synchronized before the measurements.

Equipment designation	Description	Unit
Wsp_Metmast_100m	Wind speed, 100 m	m/s
Wsp_Metmast_80m	Wind speed, 80 m	m/s
Wsp_Metmast_60m	Wind speed, 60 m	m/s
Wsp_Metmast_40m	Wind speed, 40 m	m/s
Wsp_Metmast_10m	Wind speed, 10 m	m/s
Wsp_Metmast_2m	Wind speed, 2 m	m/s
Tdiff_100M2_MetMast	Temperature difference between 100 m and 2 m	°C
Tdiff_80M2_MetMast	Temperature difference between 80 m and 2 m	°C
Tdiff_60M2_MetMast	Temperature difference between 60 m and 2 m	°C
Tdiff_40M2_MetMast	Temperature difference between 40 m and 2 m	°C
Tdiff_10M2_MetMast	Temperature difference between 10 m and 2 m	°C
Tabs_MetMast_2m	Temperature at 2 m	°C
RH_2m	Relative humidity at 2 m	%

Table 3
Meteorological data from the measurement equipment at Høvsøre used in the analysis.

The measurements were made on 11 December 2007 in the periods given in Table 4.

Source height	**Wind scenario**	
	Downwind	Upwind
50 m	12:14-13:12	15:34-16:51
30 m	13:15-14:04	16:53-17:30

Table 4
Measurement time periods.

5.1.3 Hitra

It was decided to do the wind turbine noise campaign in complex terrain, and Statkraft Development allowed the use of the wind farm at Hitra in Norway. A loudspeaker measurement campaign was conducted as well. It was possible to place the loudspeaker on a wind turbine giving a source height of 70 m above surrounding terrain, see Figure 6. The measurements were made over 2 days with downwind measurements at low wind on the first day and upwind and downwind measurements at high wind speeds on the second day. A map of Hitra wind farm is shown in Figure 5. The noise measurements were made at and around wind turbine 24 at the north end of the wind farm. The meteorology mast was positioned at the south end of the wind farm.

The terrain was very complex with changing surface conditions and large variations in terrain level as can be seen in Figure 7 and Figure 8 showing a cross-section of the measurement setup during downwind and upwind. The terrain level for the measurement positions are given in Table 5. In Figure 9 the measurement position at 800 m downwind is shown. The terrain variation was measured with a GPS by tracking the route from the wind turbine through the measurement positions to the furthest measurement position.

At Hitra the meteorological data was obtained partly as the wind speed from the nacelle anemometer and as wind speeds and temperatures from the meteorology mast at the south end of the wind farm. The wind speed from the nacelle anemometer was sampled several times per second. The data from the meteorology mast were only given as averages over 10 minute periods. The wind speeds were measured at 10, 29 and 70 m above ground, the temperature was measured at 29 m above ground and the relative humidity was measured 2 m above ground. The noise measurement systems were synchronized with the meteorological measurement system.

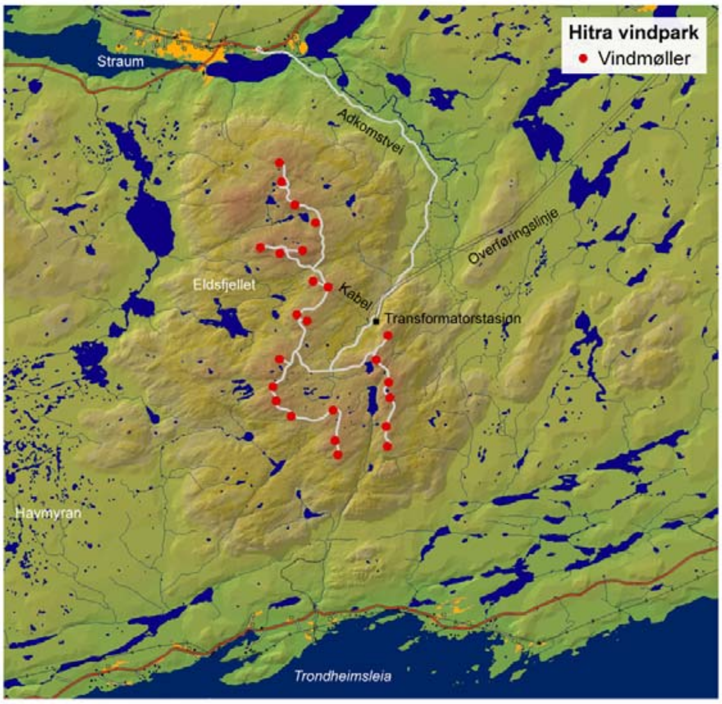

Figure 5
Hitra wind farm. The measurements were made around the wind turbine at the top of the picture. The wind was north easterly.

Figure 6
Loudspeaker position at Hitra.

Microphone position	Exact distance (m) / terrain level (m)	
	Downwind	Upwind
1	412 / 251	399 / 257
2	802 / 274	633 / 217
3	999 / 290	-

Table 5
Exact horizontal distance between loudspeaker and microphone for each microphone position and. The corresponding terrain level above sea level is included. The terrain level of the wind turbine was 290 m above sea level.

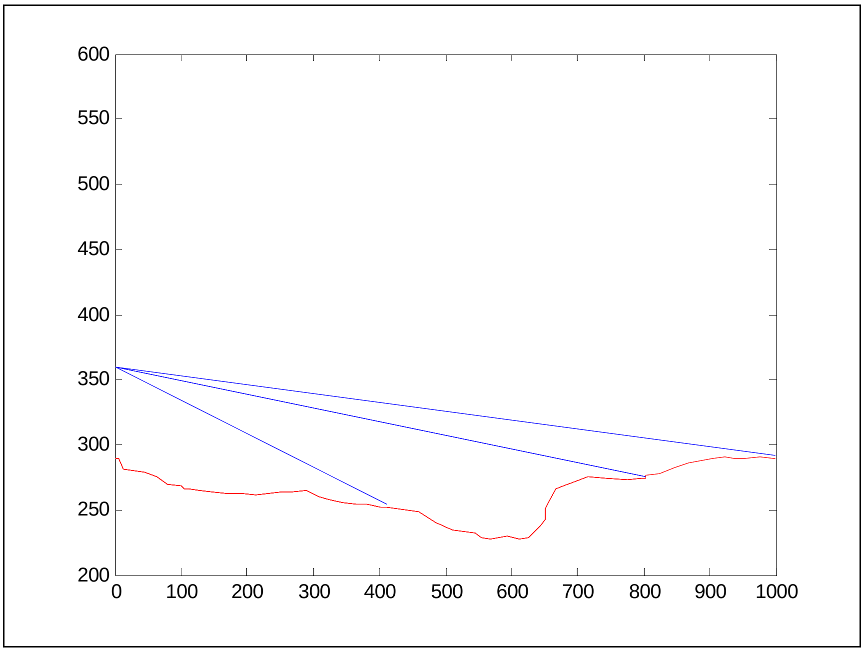

Figure 7
Cross section of the terrain for the downwind measurements. The straight blue lines indicate the line of sight from source to receiver and the red curve shows the terrain.

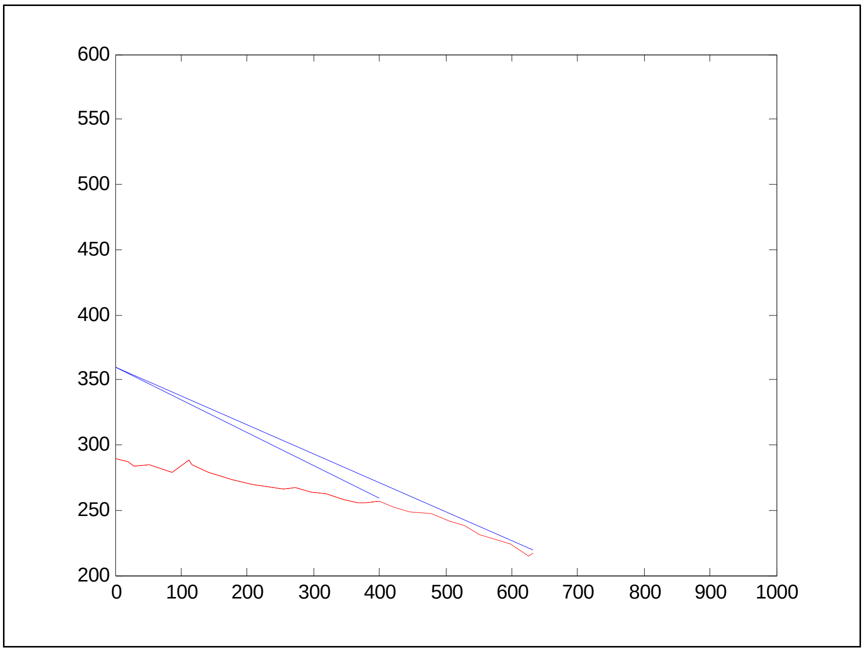

Figure 8
Cross-section of the terrain for the upwind measurements. The straight blue lines indicate the line of sight from source to receiver and the red curve shows the terrain.

Figure 9
Measurement position at 800 m downwind at Hitra.

Date	Wind scenario	
	Downwind	Upwind
8 July 2008	16:31-18:45	-
11 July 2008	15:41-16:08	13:11-14:33

Table 6
Measurement time periods.

5.2 Wind turbine noise measurements

The wind turbine noise measurement campaign was conducted at Hitra and the measurement positions were the same as for the loudspeaker measurements. The reference measurement position was on a ground board at a distance of 112 m from the wind turbine. Due to malfunction of the measurement system at the reference positions, there are no data for the upwind situation.

Date	Wind scenario	
	Downwind	Upwind
8 July 2008	16:31-18:45	-

Table 7
Measurement time periods.

5.3 Wind farm measurements

Measurements have been made at 3 positions downwind from a wind farm with around 70 wind turbines in flat terrain. Meteorology data is received from the meteorology mast at the wind farm. The wind speeds were measured at several heights, the temperature and pressure were measured at one height. Detailed information on the terrain was available as elevations lines in digital format. The ground conditions were a mix of soft ground, rocks and water.

The size of the wind farm was 4.5 times 4 km, and the measurement positions were 4 km, 3 km and 2.5 km from the nearest wind turbine. Measurement position 1 and 2 are lying in the same direction at different distances, while position 3 is in another direction. Noise predictions are made with Nord2000 for conditions corresponding to the measurement situation. Noise emission measurements were made on 2 of the wind turbines at the site according to IEC 61400-11, and these data are used in the noise predictions. The results are shown in Figure 10 to Figure 12. There is a good agreement at the lower frequencies, but at higher frequencies the background noise is dominating. Above 1 kHz only background noise is present in the measurements.

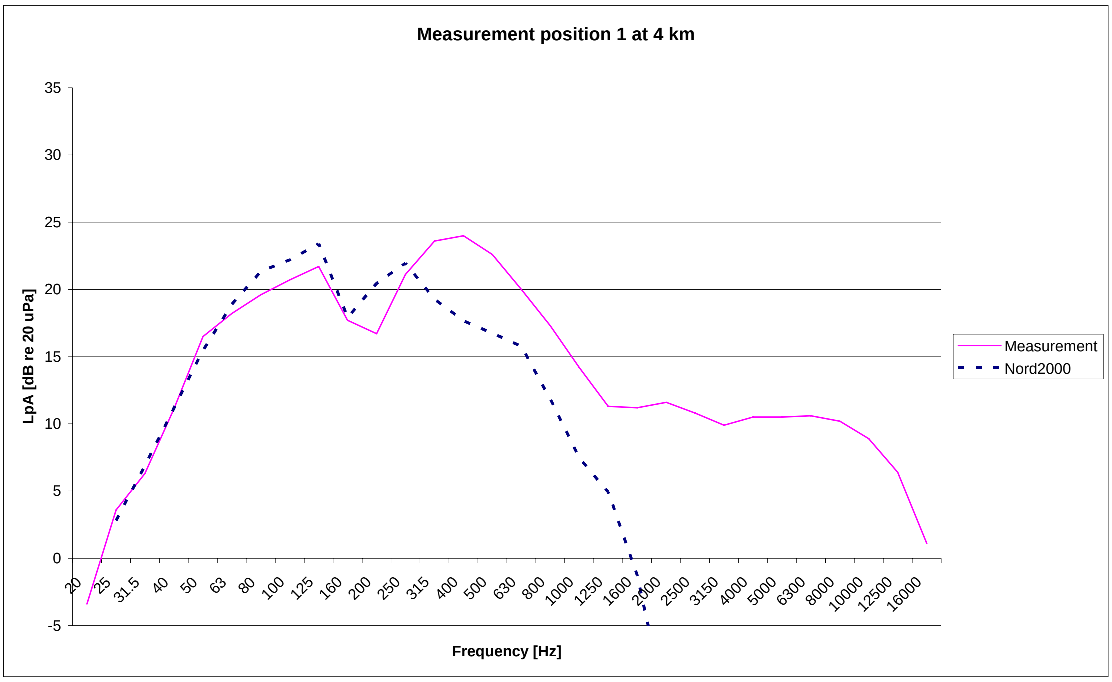

Figure 10
Downwind propagation from a wind farm, 4 km, receiver height 1.8 m.

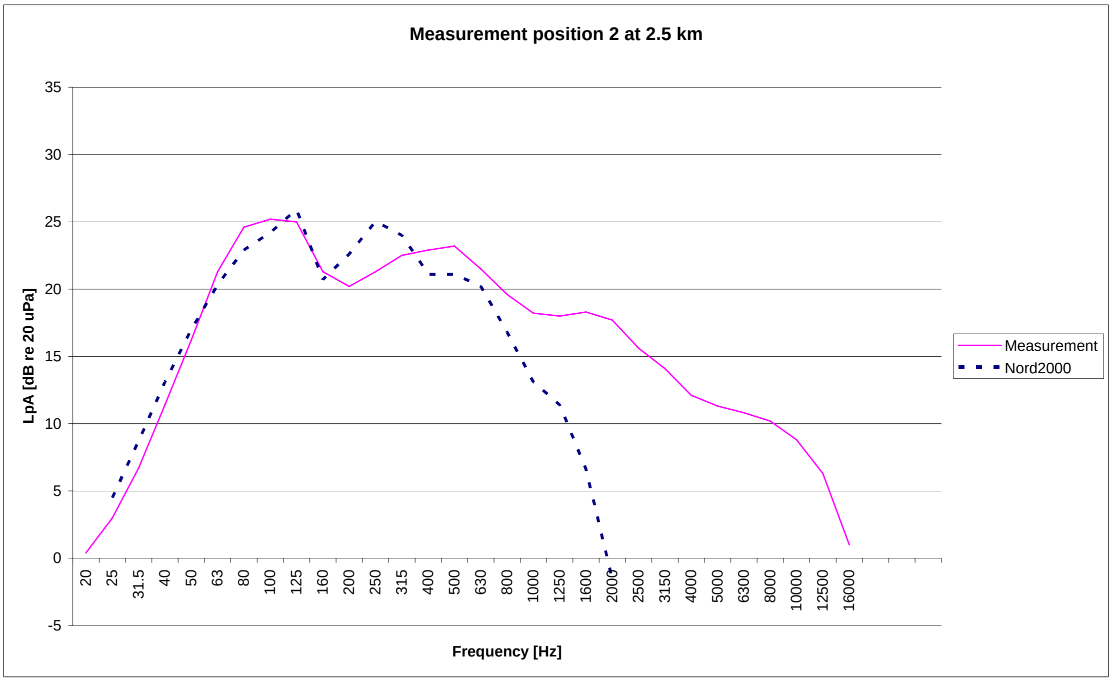

Figure 11
Downwind propagation from a wind farm, 2.5 km, receiver height 1.8 m.

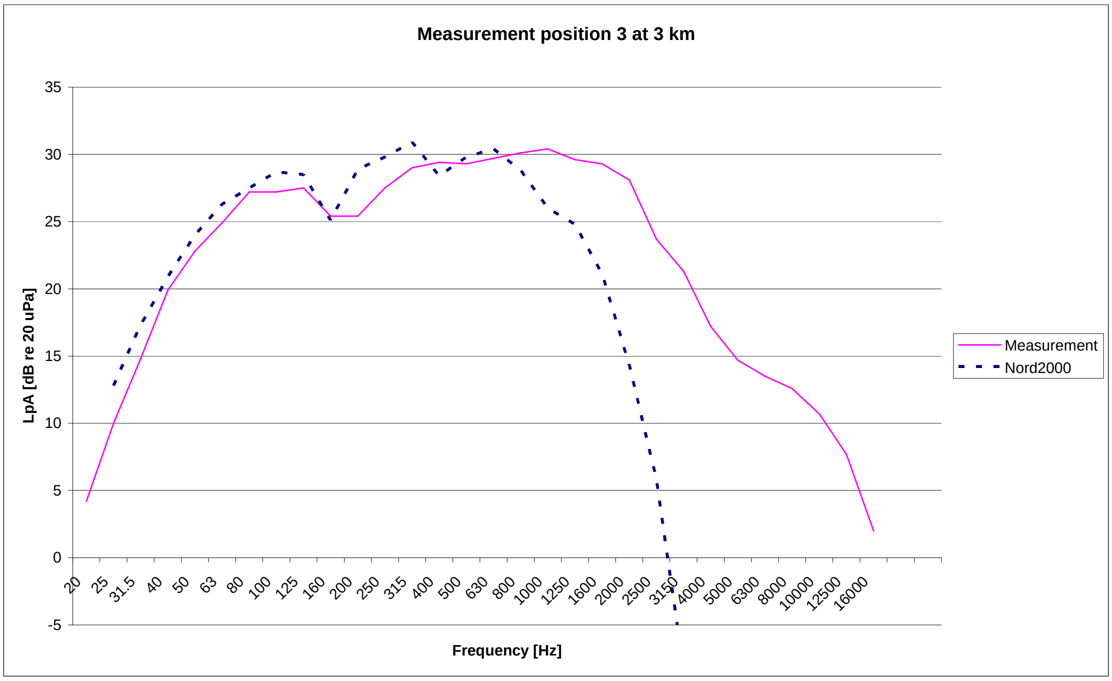

Figure 12
Downwind propagation from a wind farm, 3 km, receiver height 1.8 m

6. Data Analysis

The data analysis procedure is described below for the following experiments based on type of source and measurement location:

- Loudspeaker, flat terrain (location Høvsøre)
- Loudspeaker, complex terrain (location Hitra)
- Single wind turbine, complex terrain (location Hitra)

6.1 Analysis procedure for loudspeaker measurements at Høvsøre

In the measurement experiment at Høvsøre, measurements of sound propagating over flat grass-covered ground from a loudspeaker to a microphone were made for the following 24 propagation cases:

- Propagation during downwind or upwind.
- Horizontal propagation distances of approximately 500, 1000, and 1500 m (microphone position 1, 2, and 3).
- Source heights of 30 or 50 m above ground.
- Receiver heights of 2 or 5 m above ground.

The exact horizontal propagation distances are given in Section 5.1.2, Table 2.

The upwind recordings in microphone position 3 were not analysed due to too high background noise.

During the measurement period the signal sequences described in Table 1 were repeated a number of times.

The sound recordings were analysed by determining the equivalent sound pressure level L_{eq} in 1/3-octave bands from 50 Hz - 2.5 kHz every 10 sec. throughout the measurement period.

Signals no. 1-2 defined in Table 1 were six 1/1-octave bands wide with duration 50 sec. followed by a pause of 10 sec. This sequence produced five L_{eq}-values of sound from the loudspeaker and one L_{eq}-value with background noise. Due to slight difference in internal clock time of recording and analysis equipment, it was decided not to use the first and last L_{eq}-value but only the three values in the middle, and let the sound pressure level of the signal sequence be represented by the average value of these three. The meteorological data attached to the average sound pressure level were determined as the average value in the same 30 sec. In the following the result will shortly be denoted the wide-band result.

Signals no. 3-14 defined in Table 1 were six signals 1/1-octave band wide from 63 Hz – 2 kHz played in succession, each with duration of 50 sec. and with a pause of 10 sec. This sequence produced five L_{eq}-values of sound from the loudspeaker and one L_{eq}-value with background noise for each octave band signal. Again, due to internal clock time problem mentioned above it was decided not to use the first and last L_{eq}-value of each octave band signal but only the three values in the middle, and let the sound pressure level of the signal sequence be represented by the average value of these three. The three 1/3-octave band results of each octave band signal were used to create the full spectrum from 50 Hz - 2.5 kHz. This way the total signal duration becomes 330 sec., and the meteorological data to be attached to the sound pressure level were therefore determined as the average value in the same period. In the following the result will shortly be denoted the octave-band result.

The reason for using 10 sec. periods was that it was considered to investigate the correlation between meteorological data end noise levels on a very short term basis. However, it was found, that it was not meaningful to considered shorter periods than one signal sequence (30 sec. for wide-band results and 330 sec. for octave-band results).

The argument for using the more complicated octave band procedure was that the output from the loudspeaker could be increased by approx. 8 dB per 1/3-octave band which improves the signal-to-noise-ratio. However, the wide-band and octave-band results did not show any significant differences, and in the analysis it was therefore decided not to distinguish between the two kinds of results. Therefore, the number of sequences contained in the analysis specified below is the total number of wide-band and octave-band sequences.

The number of signal sequences in the analysis for measurement position 1 and 2 are shown in Table 8. For measurement position 3 during downwind propagation the number was the same for source 30 m, while the number of sequences was 1 less for receiver height 2 m and 3 less for receiver height 5 m. For measurement position 3 the upwind recordings were not analyzed due to an insufficient signal-to-noise-ratio.

Source height	Downwind	Upwind
30 m	15	11
50 m	15	22

Table 8
Number of spectra from the analysis (number of wide- or octave-band signal sequences) for measurement position 1 and 2.

To determine the sound power emitted from the loudspeaker the sound pressure level were measured approximately 1 m from the loudspeaker front. The short distance was chosen for practical reasons taking into account that the loudspeaker should to be lifted up to a height of 50 m. However, the short distance introduced some uncertainties as the acoustical centre of the loudspeaker cannot be expected to be at the front of the loudspeaker. Furthermore, the loudspeaker was equipped with two loudspeaker units giving a near field error in the measurement. A better approach would have been to determine the sound power level in an anechoic chamber based on measurement in a larger distance, where the uncertainty due to the position of the acoustical centre and near field error could be reduced but this was not possible within the project. However, based on best judgment the results have been corrected for the displacement of the acoustical centre and for a near field effect. It is estimated that the uncertainty due to this correction is less than 1 dB. When the correction is applied the average deviation between measured and predicted values becomes close to 0 dB at the nearest microphone position (Pos. 1).

To compare the measured excess propagation effect with prediction by Nord2000, the excess propagation effect $\Delta L(f)$ has to be estimated by Eq. (1) where $L(f)$ is the measured 1/3-octave band sound pressure level and $L_0(f)$ and is the free field sound pressure level. The excess propagation effect determined by Eq. (1) contains the propagation effect of ground and air absorption.

$$\Delta L(f) = L(f) - L_0(f) \tag{1}$$

The free field sound pressure level $L_0(f)$ is determined by Eq. (2) where $L_{1\text{m}}(f)$ is the sound pressure level measured approximately 1 m from the loudspeaker front. d is distance from the loudspeaker to the receiver and d_0 is distance from the acoustical centre of the loudspeaker to the “1m” microphone including the correction for near field effect. A value of d_0 = 1.29 m has been found to provide the best estimate.

$$L_0(f) = L_{1m}(f) - 20\log\left(\frac{d}{d_0}\right) \tag{2}$$

The meteorological data were also recorded every 10 sec. as described in Section 5.1.2 and include the wind speed (in m/s) and temperature (in °C) measured 2, 10, 40, 60, 80, and 100 m above the ground surface. The relative humidity (in %) was measured at 2 m. The wind direction was also measured at a number of heights, but the wind direction was so close to the direction of propagation that it could be assumed, that the wind speed component in the direction of propagation was equal to the wind speed (the inverse of the wind speed in upwind).

In Nord2000 the calculations are based on the vertical effective sound speed profile, which can be estimated on basis of the vertical wind speed profile and the temperature profile. The vertical effective sound speed c(z) at height z has to be approximated by the log-lin profile in Eq. (3), where A, B, and C are constants and z_0 is the average roughness length of the terrain surface.

$$c(z) = A \ln\left(\frac{z}{z_0} + 1\right) + B\,z + C \tag{3}$$

The effective sound speed c(z) at the height z above ground can be determined by Eq. (4) where u(z) and t(z) are the wind speed and temperature at height z. Δν is the angle between the wind direction and the direction of propagation (Δν = 0° in downwind and Δν = 180° in upwind).

$$c(z) = u(z)\cos(\Delta v) + 20.05\sqrt{t(z) + 273.15} \tag{4}$$

In the Høvsøre experiment the vertical effective sound speed profile has been determined by calculating c(z) at the six heights where wind and temperature were measured. A, B, and C has then been determined by a least-squares-fit using z_0 = 0.05 m. As mentioned earlier average values of wind and temperature were used corresponding to the part of the signal sequence used in the analysis (30 sec. for wide-band results and 330 sec. for octave-band results). More information concerning the agreement between the actual measured effective sound speed profile and the estimated log-lin profile can be found in Annex A.

Further assumptions in the Nord2000 predictions are, that the ground is flat with surface properties corresponding to a flow resistivity of 200 $kPas^{-2}$ (grass-covered ground) and that the turbulence constants are C_v^2 = 0.012 $m^{4/3}s^{-2}$ and C_T^2 = 0.0008 Ks^{-2}.

In the analysis the measured and predicted excess propagation effect spectra *ΔL(f)* have been determined for each signal sequence. For each propagation case defined above, these spectra have been used to determine the average spectra and the average A-weighted sound pressure level in order to compare measured and predicted average values for each propagation case. The A-weighted sound pressure level is determined on basis of the estimated excess propagation effect spectra and a typical wind turbine power spectrum.

6.2 Analysis procedure for loudspeaker measurements at Hitra

In the measurement experiment at Hitra propagation took place over non-flat terrain where parts of the ground were covered with grass and other parts were open bedrock so that the surface was a mix of acoustically soft and hard surfaces.

The measurement procedure was in many respects similar to the Høvsøre experiment except that the loudspeaker was placed on top of a wind turbine nacelle giving only one source height (70 m above ground). Therefore, measurements were made for the following 10 propagation cases:

- Propagation during downwind or upwind.

- Three measurement positions, Pos. 1, 2, and 3, placed downwind corresponding to horizontal distances of approximately 400, 800, and 1000 m.

- Two measurement positions, Pos. 1 and 2, placed upwind corresponding to horizontal distances of approximately 400 and 600 m.

- Receiver heights of 2 or 5 m above ground.

The measurements in downwind propagation were carried out on two measurement days (8 July and 11 July), but on the second day measurements were only carried out at Pos. 1 and 2 using a receiver height of 2 m.

The sound recordings were analysed using the same method as in the Høvsøre experiment based on equivalent sound pressure level L_{eq} in 1/3-octave bands from 50 Hz - 2.5 kHz every 10 sec. period throughout the measurement period. One difference was that the use of periods no. 2-4 in the wide-band or octave-band signal sequence to determine the average L_{eq}-value was changed to periods no. 3-5 because it was found that the first two periods were affected by the difference in internal clock time of recording and analysis equipment. Another difference was the use of microphone placed in front of the loudspeaker. In the Hitra experiment it was assumed, that the sound power level was the same as determined in the Høvsøre experiment and the microphone was only used to ensure, that emitted noise did not change during the experiment.

In measurement Pos. 1 during both downwind and upwind propagation the elevation angle of the loudspeaker seen from the measurement position was approximately 15°. The directivity of the loudspeaker at this angle is known to be significant at high frequencies. Therefore, the measured excess ground effect result in Pos. 1 has been adjusted for the directivity pattern above 500 Hz as described in Annex D. Another problem in Pos. 1 was that the nacelle has a cylindrical shape with a diameter of 2.7 m, where the loudspeaker was placed. At an emission angle of 15° this will most likely cause a significant reflection in the nacelle body. However, at smaller emission angles (Pos. 2 and 3) the reflection is expected to be insignificant. This assumption was supported by all observed results in Pos. 1 (both downwind and upwind), which showed that the measured excess ground effect was approximately 3 dB higher than the predicted when the reflection was ignored. Therefore, in the presented results for Pos. 1 the sound power level has been adjusted by 3 dB independent of the frequency to account for the reflection. It has not been possible within the project to verify this adjustment neither experimentally nor theoretically.

The meteorological data were not as extensive as in the Høvsøre experiment but were only available every 10 minute as averaged values. Wind speed and direction were only measured 10, 29, and 70 m above the ground surface and the temperature was measured at 29 m. The relative humidity was measured 2 m above ground. As the temperature was only available at one height, the temperature profile has been estimated using the Businger-Dyer equation assuming an unstable atmosphere with a Monin-Obukhov length of L = -14 and a ground roughness length of z_0 = 0.05 m. The Monin-Obukhov length was estimated on basis of the time of the measurements, the cloud cover, and the wind speed. The effective sound speed was determined at heights 10, 29, and 70 m according to Eq. (4). The temperature in the equation was the estimated value using the Businger-Dyer equation. In the same way as in the Høvsøre experiment A, B, and C in Eq. (3) have been determined by a least-squares-fit using z_0 = 0.05 m. In the analysis the effective sound speed profile were assumed to be constant within the 10 minute period.

The estimated effective sound speed profiles are shown in Annex C. Figure 54 to Figure 56 in the annex shows the estimated effective sound speed profile for each signal sequence during the measurement periods of following propagation cases:

- Downwind propagation, first measurement day (8 July)
- Downwind propagation, second measurement day (11 July)
- Upwind propagation, second measurement day (11 July)

Figure 54 and Figure 55 for downwind propagation show that the effective sound speed is decreasing with the height above 10-20 m. This is unusual for downwind propagation, where the sound speed normally is increasing with the height. In the present case it is the result of a decrease in wind speed up to 70 m. It is assumed that the decrease in wind speed is the result of a speed-up effect cased by the topographical conditions. The implication is that propagation effects normally seen during upwind propagation may be observed during downwind. Figure 56 for the upwind propagation shows that the effective sound speed is increasing slightly at height above 30-40 m. This is also unusual for upwind propagation, where the sound speed normally is decreasing with the height. The implication is that the propagation effects normally seen during upwind may disappear and at least be very weak.

The terrain cross-section between the foot of the wind turbine with the loudspeaker and the microphone position was measured using a GPS. The terrain cross-sections are shown in Section 5.1.3. The vertical resolution of the GPS was 1 m. This was in most cases a sufficient resolution when calculating the propagation effect by Nord2000. However, in a few cases, where the resolution caused a jump in the terrain height close to the microphone, it had an adverse effect on the predicted result. In these cases the terrain information was smoothed manually.

Further assumptions in the Nord2000 predictions were that ground surface has a flow resistivity of 200 $kPas^{-2}$ (grass-covered ground) and that the turbulence constants are $C_v^2 = 0.12\ m^{4/3}s^{-2}$ and $C_T^2 = 0.008\ Ks^{-2}$. Parts of the terrain were harder than corresponding to the used flow resistivity, but for practical reasons it was difficult to model the variation in ground surface properties along the terrain cross-sections. In the analysis the effect of changing the flow resistivity to a higher value was investigated but showed only a small effect on the predicted result.

In the same way as in the Høvsøre analysis the measured and predicted excess propagation effect spectra $\Delta L(f)$ have been determined for each signal sequence. For each propagation case defined above, these spectra have been used to determine the average spectra and the average A-weighted sound pressure level in order to compare measured and predicted average values for each propagation case. The A-weighted sound pressure level is determined on basis of the estimated excess propagation effect spectra and a typical wind turbine power spectrum.

6.3 Analysis procedure for wind turbine measurements at Hitra

In the wind turbine experiment at Hitra the measurement setup was generally the same as used in the loudspeaker experiment except, that the sound source was the wind turbine on which the loudspeaker was placed in the loudspeaker experiment. The sound power level of the wind turbine was less than the sound power level of the loudspeaker and the recordings from Pos. 3 have not been analysed due to too much background noise. Due to technical problems in the experiment it was not possible to analyse the upwind recordings. One major difference in measurement setup compared to the loudspeaker experiment was, that the sound power level of the wind turbine was determined for each 10 sec. period in the analysis based on a measurement 111 m from the wind turbine according to IEC 61400-11:2002 ed. 2.1 [7].

In the analysis the measured and predicted excess propagation effect spectra $\Delta L(f)$ have been determined for each 10 second period. The same procedure has been used to determine the corresponding effective sound speed profiles as in the loudspeaker experiment where it was assumed that the effective sound speed profile were constant in the 10 minute meteorological observation period. For each of the 4 propagation cases (Pos. 1 and 2, receiver height 2 and 5 m) the measured and predicted average spectra and A-weighted sound pressure levels have been determined. The A-weighted sound pressure level has been determined on basis of the excess propagation effect spectra and a typical wind turbine power spectrum as in the other experiments.

7. Results

The result of the data analysis is shown below for each combination of type of source and measurement location.

7.1 Result of loudspeaker measurements at Høvsøre

As mentioned in Section 6.1 the measured and predicted excess propagation effect spectra $\Delta L(f)$ have been determined for each signal sequence. These spectra have subsequently been used to determine the average excess propagation effect spectra and A-weighted propagation effect for each of the propagation cases:

- Propagation during downwind or upwind.
- Horizontal propagation distances of approximately 500, 1000, and 1500 m (microphone position 1, 2, and 3).
- Source heights of 30 or 50 m above ground.
- Receiver heights of 2 or 5 m above ground.

The results for downwind and upwind propagation are shown below in Section 7.1.1 and 7.1.2, respectively.

7.1.1 Downwind propagation

Typical results for downwind propagation are shown in Figure 13 and Figure 14. All results for the downwind propagation cases can be seen in Annex B. The agreement between measured and predicted spectra is in general good.

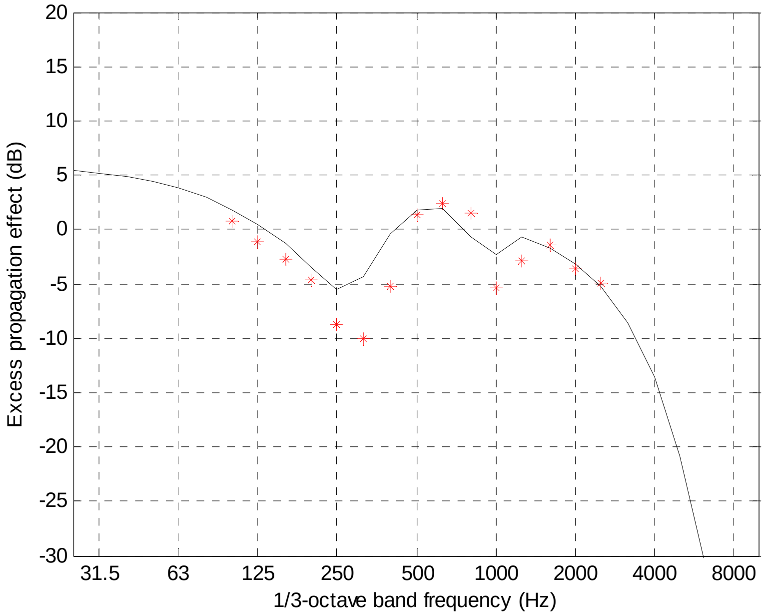

Figure 13
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 500 m, source height 30 m, and receiver height 2 m.

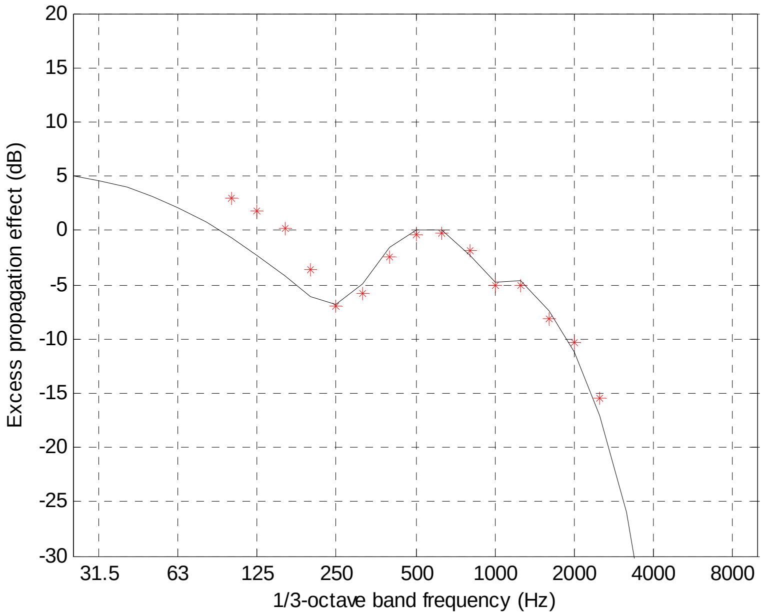

Figure 14
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1500 m, source height 50 m, and receiver height 2 m.

The measured and predicted A-weighted excess propagation effects in the downwind experiment and the difference between predicted and measured values are shown in Table 9. The table also shows the number of signal sequences included in the average values. The average deviation is -0.1 dB with a standard deviation of 0.7 dB so the agreement is very fine. The result is presented graphically in Figure 15.

Pos.	**h_S (m)**	**h_R (m)**	**Number of seq.**	**Nord2000 (dB)**	**Measured (dB)**	**ΔL_A(c-m) (dB)**
1	30	2	15	-1.4	-2.1	0.7
1	30	5	15	0.0	1.2	-1.2
1	50	2	15	-1.1	-1.4	0.3
1	50	5	15	0.4	0.1	0.3
2	30	2	15	-3.3	-4.0	0.7
2	30	5	15	-1.3	-1.6	0.3
2	50	2	15	-2.7	-3.2	0.5
2	50	5	15	-1.0	-0.9	-0.1
3	30	2	15	-4.3	-3.2	-1.1
3	30	5	15	-2.0	-1.4	-0.6
3	50	2	13	-3.9	-3.0	-0.9
3	50	5	9	-1.6	-1.5	-0.1
Total					Average	-0.1
					Std. dev.	0.7

Table 9
Measured and predicted A-weighted excess propagation effect. Downwind propagation over flat terrain from a loudspeaker at Høvsøre.

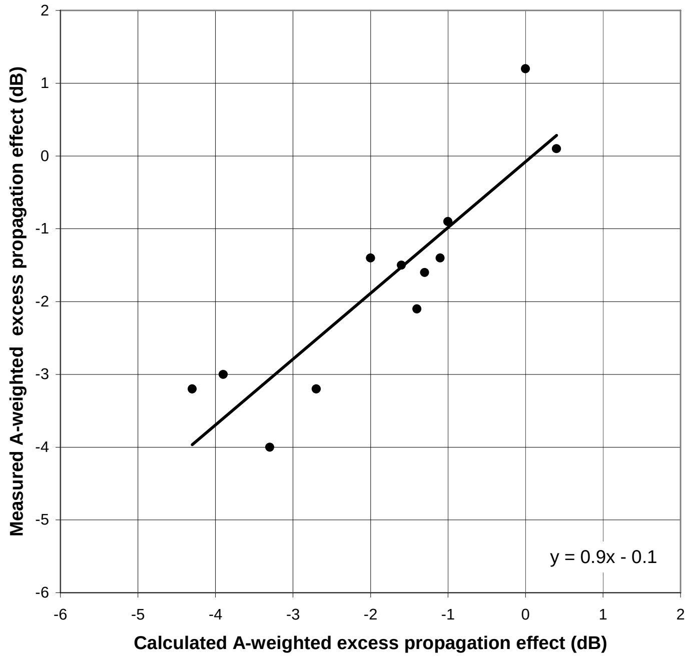

Figure 15
Measured versus predicted A-weighted excess propagation effect in the downwind experiment at Høvsøre (circles are A-weighted results, the line is a linear fit to the results given by the equation in the lower right part of the figure).

7.1.2 Upwind propagation

Typical results for upwind propagation are shown in Figure 16 and Figure 17. All results for the upwind propagation cases can be seen in Annex B. The agreement between measured and predicted spectra is in general less good than seen for downwind propagation. Figure 16 shows the result at a propagation distance of 1000 m for the lowest source position and receiver height. In this case the upwind is causing a considerable acoustically shadow zone effect with large attenuation at high frequencies. Taking into account how unstable such shadow zones are it is fairly well modelled by Nord2000. In Figure 17 where the source is at the highest position instead the measurement shows a slightly reduced attenuation compared to the low source position whereas Nord2000 predicts a much larger reduction. The general trend in the upwind measurement experiment is that measurement and prediction in some cases agree to show an effect of a shadow zone effects and in other cases agree to show no shadow zone effect. However, in a number cases shadow zone effects are seen in the measurements but not in the predictions, whereas the opposite is not seen in the experiment.

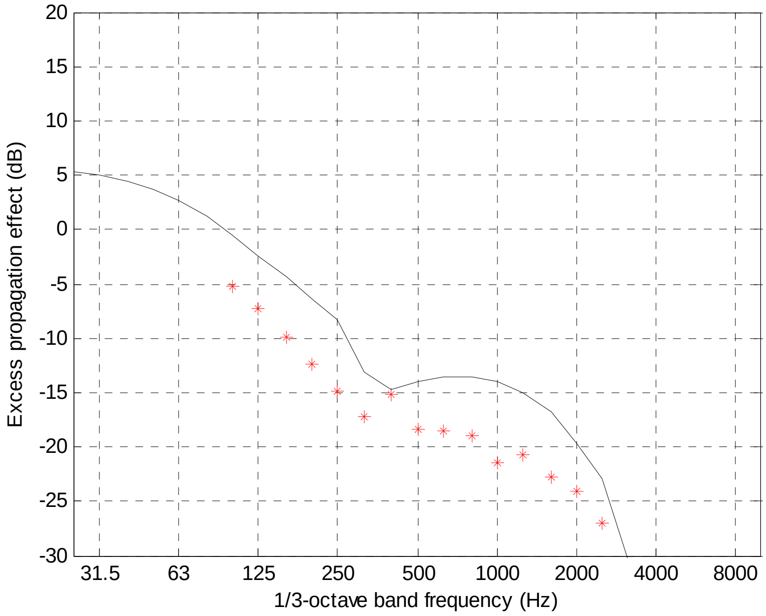

Figure 16
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 1000 m, source height 30 m, and receiver height 2 m.

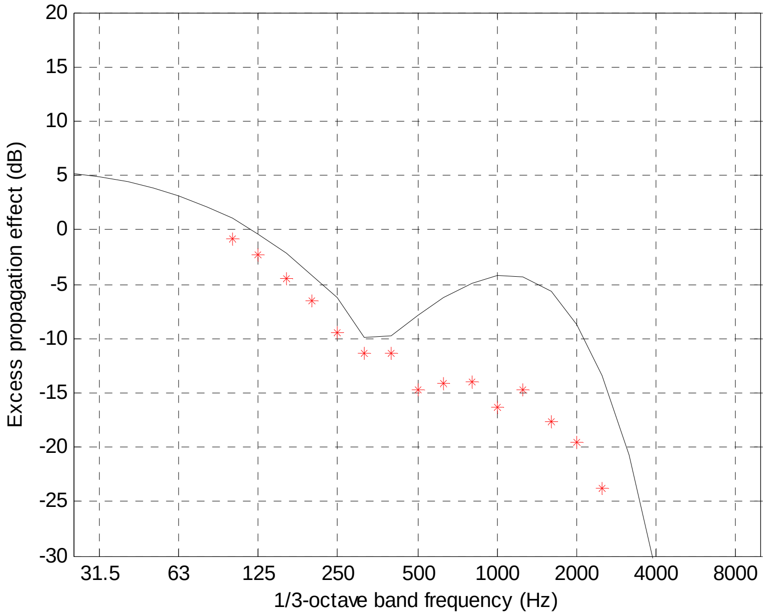

Figure 17
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 1000 m, source height 50 m, and receiver height 2 m.

The measured and predicted A-weighted excess propagation effects in the upwind experiment and the difference between predicted and measured values are shown in Table 10. The table also shows the number of signal sequences included in the average values. The average deviation is 4.3 dB with a standard deviation of 1.9 dB. The result is presented graphically in Figure 18. Although the agreement is poor compared to the downwind results it is considered acceptable taking into account the well-known difficulties of making accurate prediction for an acoustical shadow zone in upwind. It is possible, that the Nord2000 method could be adjusted to decrease the average deviation in upwind, but on the existing basis it is considered better to have a conservative method. An adjustment would require a much more extensive number of measurements.

Pos.	**h_S (m)**	**h_R (m)**	**Number**	**Nord2000 (dB)**	**Measured (dB)**	**ΔL_A(c-m) (dB)**
1	30	2	11	-0.8	-8.9	8.1
1	30	5	11	-0.6	-3.1	2.5
1	50	2	22	-1.2	-3.8	2.6
1	50	5	22	0.2	-2.1	2.3
2	30	2	11	-9.4	-14.6	5.2
2	30	5	11	-6.9	-11.5	4.6
2	50	2	22	-5.2	-9.5	4.3
2	50	5	22	-3.3	-8.0	4.7
Total					Average	4.3
					Std. dev.	1.9

Table 10
Measured and predicted A-weighted excess propagation effect. Upwind propagation over flat terrain from a loudspeaker at Høvsøre.

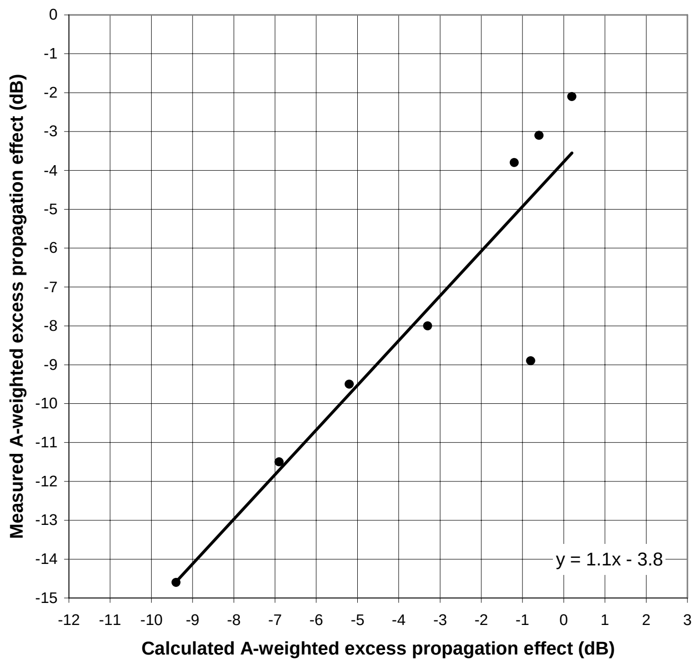

Figure 18
Measured versus predicted A-weighted excess propagation effect in the upwind experiment at Høvsøre (circles are A-weighted results, the line is a linear fit to the results given by the equation in the lower right part of the figure).

7.2 Result of loudspeaker measurements at Hitra

As in the Høvsøre experiment measured and predicted excess propagation effect spectra $\Delta L(f)$ have been determined for each signal sequence and subsequently used to determine the average excess propagation effect spectra and A-weighted propagation effect for each propagation case:

- Three measurement positions placed downwind, Pos. 1, 2, and 3, corresponding to horizontal distances of approximately 400, 800, and 1000 m on the first measurement day (July 8). The second measurement day only included Pos. 1 and 2.

- Two measurement positions placed upwind, Pos. 1 and 2, corresponding to horizontal distances of approximately 400 and 600 m on the second measurement day (11 July).

- Receiver heights of 2 or 5 m above ground (only 2 m in downwind on the second day).

Results from the downwind measurement in Pos. 1, 2, and 3 on the first day are shown in Figure 19 to Figure 21 for receiver height 2 m. Results for all propagation cases can be seen in Annex D. The agreement between measured and predicted spectra is in general good. In Figure 19 minor irregular deviations are seen at high frequencies probably caused by the uncertainty in the loudspeaker directivity. The result shown in Figure 21 is particularly interesting, because considerable attenuation is observed in most of the frequency range which is unusual in downwind propagation. As mentioned earlier this attenuation, which is similar to what can be observed in upwind, is interpreted as being the result of a speed-up effect on the wind speed profile. The results for downwind propagation in the cases repeated on the second measurement day agreed well with the results of the first day. Figure 22 shows a result from the upwind measurement in Pos. 1 with a receiver height of 2 m. The agreement between measured and predicted excess ground attenuation is good in this case and the result looks more like what is observed in downwind propagation, which again may be explained by the speed-up effect.

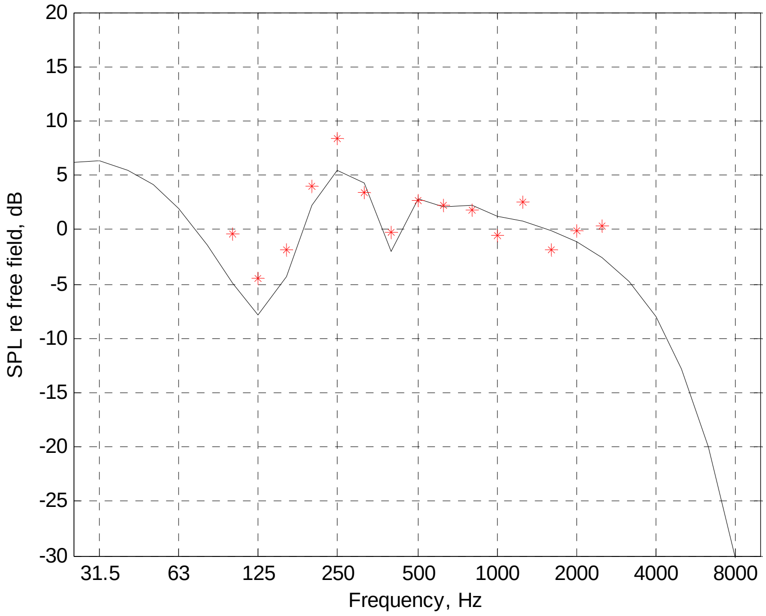

Figure 19
Downwind propagation, 8 July, Pos. 1, receiver height 2 m.

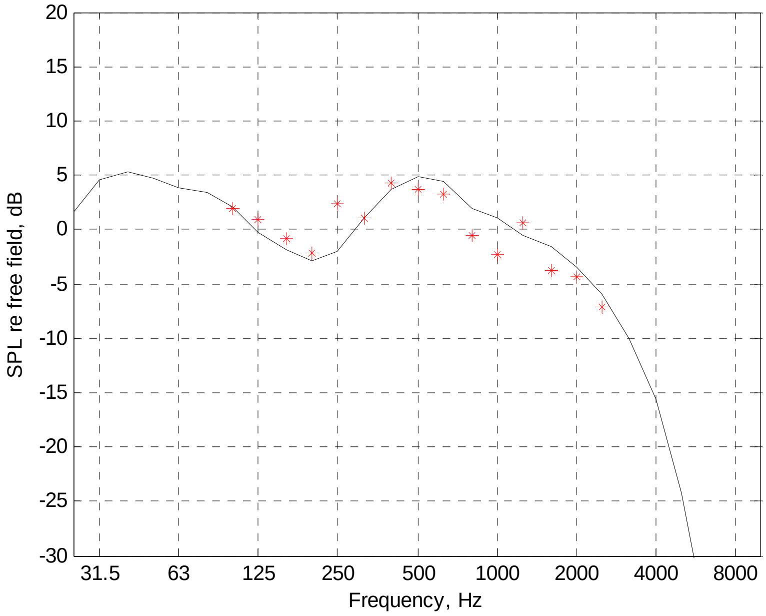

Figure 20
Downwind propagation, 8 July, Pos. 2, receiver height 2 m.

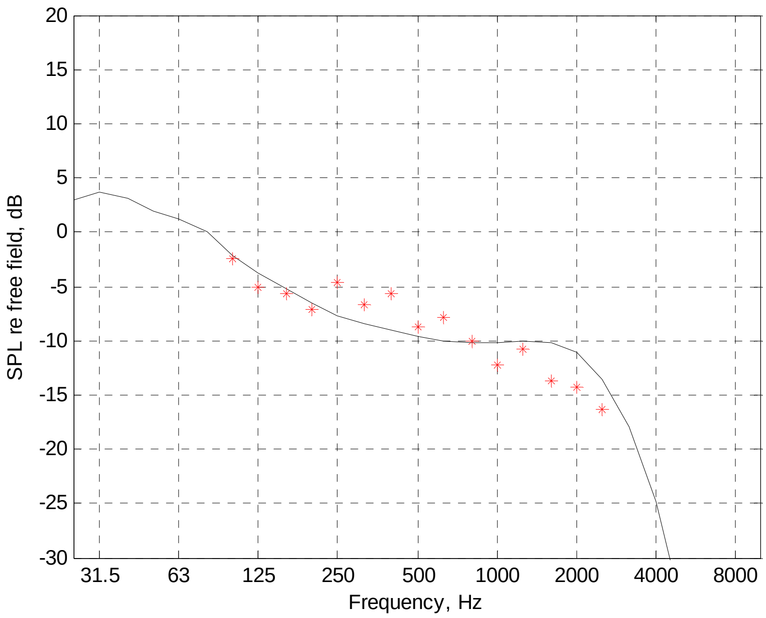

Figure 21
Downwind propagation, 8 July, Pos. 3, receiver height 2 m.

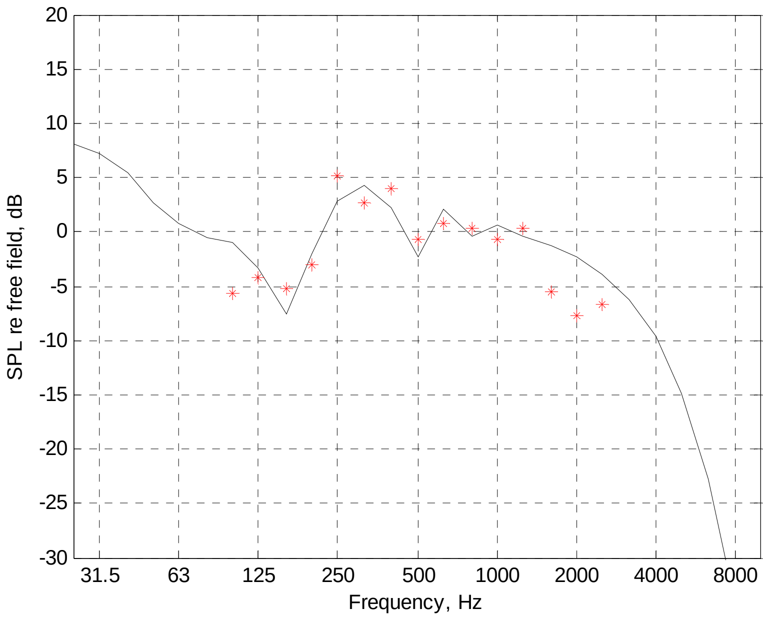

Figure 22
Upwind propagation, 11 July, Pos. 1, receiver height 2 m.

The measured and predicted A-weighted excess propagation effects in the Hitra experiment and the difference between predicted and measured values are shown in Table 11 for each propagation case and measurement day. The table also shows the number of signal sequences included in the average values. The average deviation of all results is -0.5 dB with a standard deviation of 1.8 dB, which is a satisfactory agreement taking into account the complexity of the propagation. The result is presented graphically in Figure 23.

Case	Pos.	h_R (m)	Number	Nord2000 (dB)	Measured (dB)	ΔL_A(c-m) (dB)	Group ΔL_A (dB)
Downwind 8 July	1	2	31	2.0	3.2	-1.2	-1.6
	1	5	31	0.0	2.9	-2.9	
	2	2	31	0.8	1.8	-1.0	
	2	5	32	0.4	3.7	-3.3	
	3	2	32	-8.2	-5.6	-2.6	
	3	5	32	-2.3	-3.5	1.2	
Downwind 11 July	1	2	4	2.4	1.9	0.5	0.2
	2	2	6	1.4	1.5	-0.1	
Upwind 11 July	1	2	15	0.6	0.9	-0.3	0.9
	1	5	15	2.6	0.3	2.3	
	2	2	18	-5.1	-7.2	2.1	
	2	5	18	-1.7	-1.3	-0.4	
Total						Average	-0.5
						Std. dev.	1.8

Table 11
Measured and predicted A-weighted excess propagation effect from propagation over non-flat terrain from a loudspeaker at Hitra.

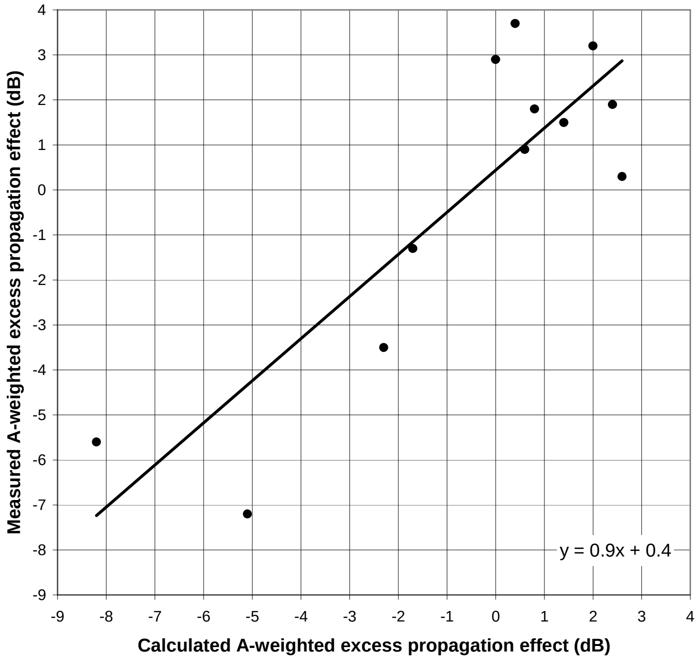

Figure 23
Measured versus predicted A-weighted excess propagation effect in the Hitra loudspeaker experiment (circles are A-weighted results, the line is a linear fit to the results given by the equation in the lower right part of the figure).

7.3 Result of wind turbine measurements at Hitra

As in the Høvsøre experiment measured and predicted excess propagation effect spectra $\Delta L(f)$ have been determined for each signal sequence and subsequently used to determine the average excess propagation effect spectra and A-weighted propagation effect for each propagation case. The propagations cases were the same as in the loudspeaker experiment but the downwind recordings in Pos. 3 were not analyzed due to too much background noise and the upwind recordings could not be used due to technical problems.

The results from the downwind measurements in Pos. 1 and 2 and receiver height 2 and 5 m are seen in Figure 24 through Figure 27.

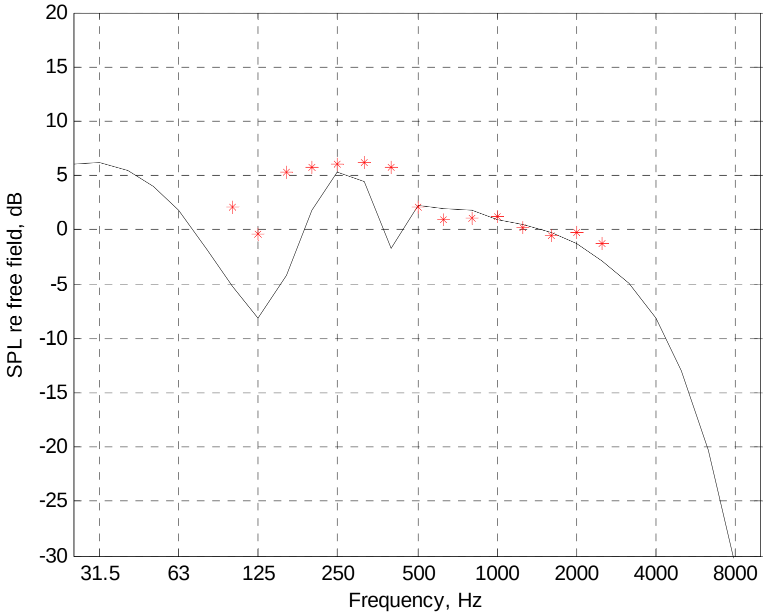

Figure 24
Downwind propagation from wind turbine, Pos. 1, receiver height 2 m.

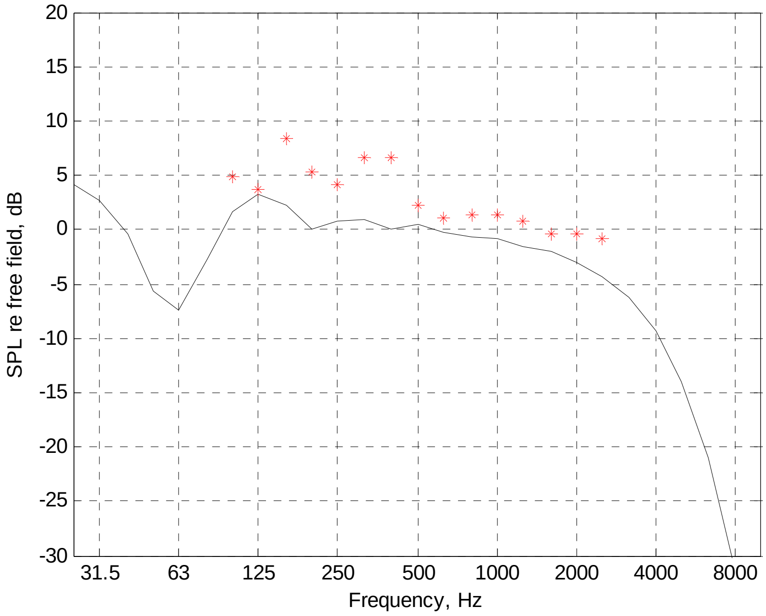

Figure 25
Downwind propagation from wind turbine, Pos. 1, receiver height 5 m.

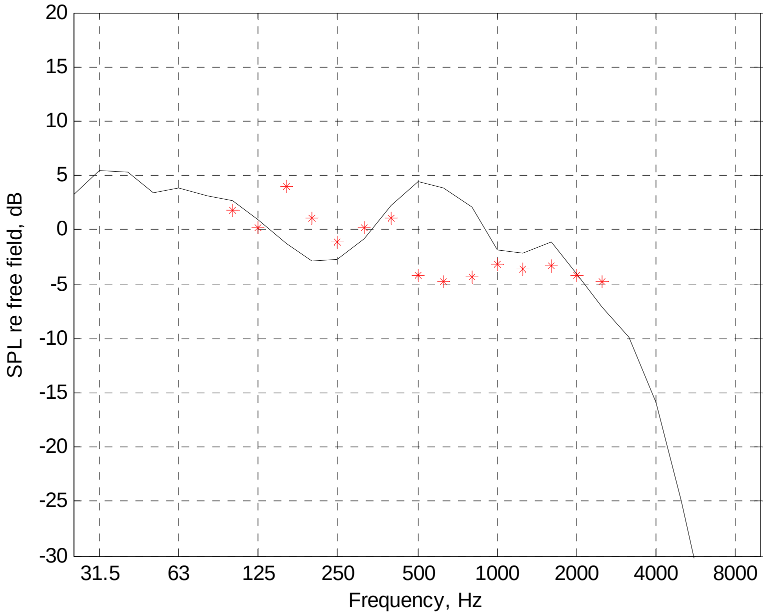

Figure 26
Downwind propagation from wind turbine, Pos. 2, receiver height 2 m.

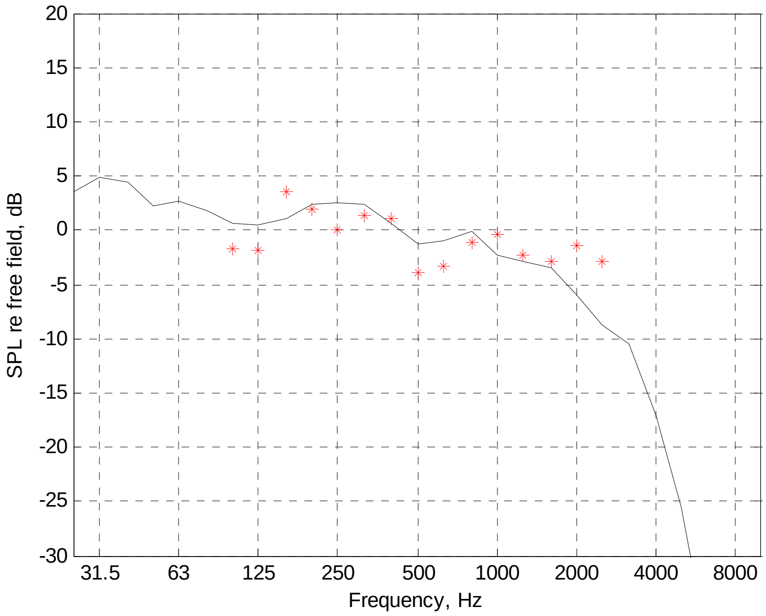

Figure 27
Downwind propagation from wind turbine, Pos. 2, receiver height 5 m.

The measured and predicted A-weighted excess propagation effects in Hitra wind turbine experiment and the difference between predicted and measured values are shown in Table 12 for each propagation case. The table also shows the time period included in the average values (number of 10 second periods times 10). The average deviation of all results is -1.0 dB with a standard deviation of 2.3 dB.

Although both the spectral results shown in the four figures and the statistics from Table 12 indicate larger deviations than seen in the loudspeaker experiment the agreement between measured and predicted is still acceptable. The determination of the sound power level of the wind turbine by the IEC 61400-11 method and the decrease in signal-to-noise-ratio will unavoidable reduce the accuracy in the analysis.

Pos.	**h_R (m)**	**Duration (sec)**	**Nord2000 (dB)**	**Measured (dB)**	**ΔL_A(c-m) (dB)**
1	2	6180	1.8	3.5	-1.7
1	5	4400	0	3.8	-3.8
2	2	2520	0.2	-1.1	1.3
2	5	2890	0.1	-0.3	0.4
Total				Average	-1.0
				Std. dev.	2.3

Table 12
Measured and predicted A-weighted excess propagation effect from propagation over non-flat terrain from a wind turbine at Hitra.

8. Nord2000 versus ISO-9613-2

A very interesting subject is how results predicted by Nord2000 will deviate from the prediction by ISO-9613-2, which is the most commonly used method for wind turbine prediction today.

It has not been possible within this project to perform a comparison for all results, but a few cases have been selected to illustrate the difference between the two prediction methods. The two selected cases are from Section 7.1.1 with downwind propagation over flat grass-covered ground at Høvsøre. Except for the high source position the ISO method is supposed to be valid in this propagation case. Figure 28 and Figure 29 correspond to the results shown in Figure 13 and Figure 14 of Section 7.1.1, but as the results predicted by the ISO method are in octave bands, the measured and calculated excess propagation effect from the figures have been converted into octave bands as well. The two figures show a much better agreement between measurements and predictions by Nord2000 than by ISO 9613-2 at the frequencies 500 and 1000 Hz important to the A-weighted levels. This is a well-known experience from using the ISO method for very high source positions. Larger deviations in the prediction would of course have been observed if the ISO method had been used to predict some of the cases where the method is not valid such as the up-wind cases at Høvsøre and some of the complex terrain cases at Hitra.

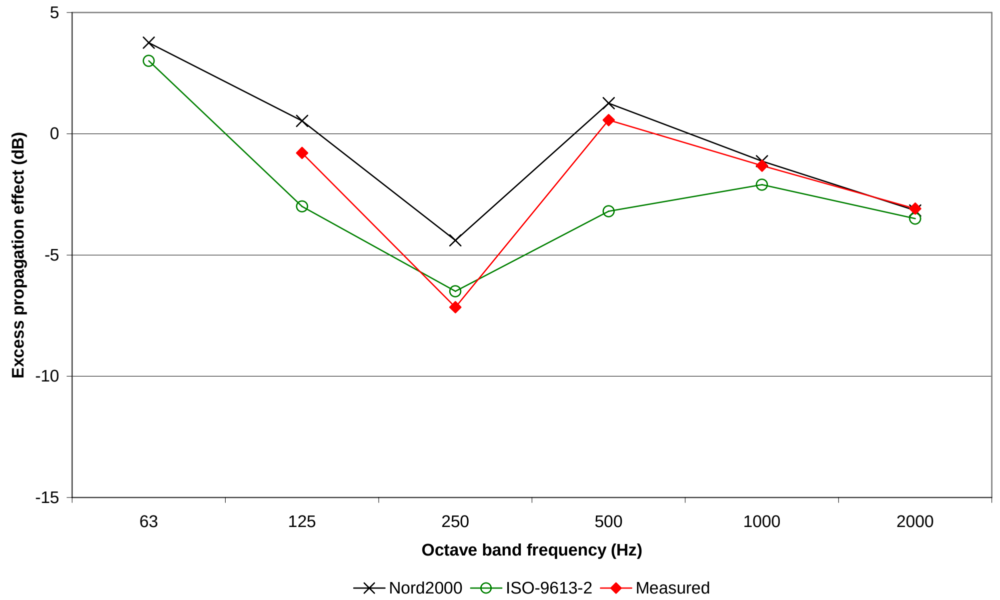

Figure 28

Excess propagation effect predicted by Nord2000 (X black), by ISO 9613-2 (○ green), and measured (♦ red). Downwind, distance 500 m, source height 30 m, and receiver height 2 m.

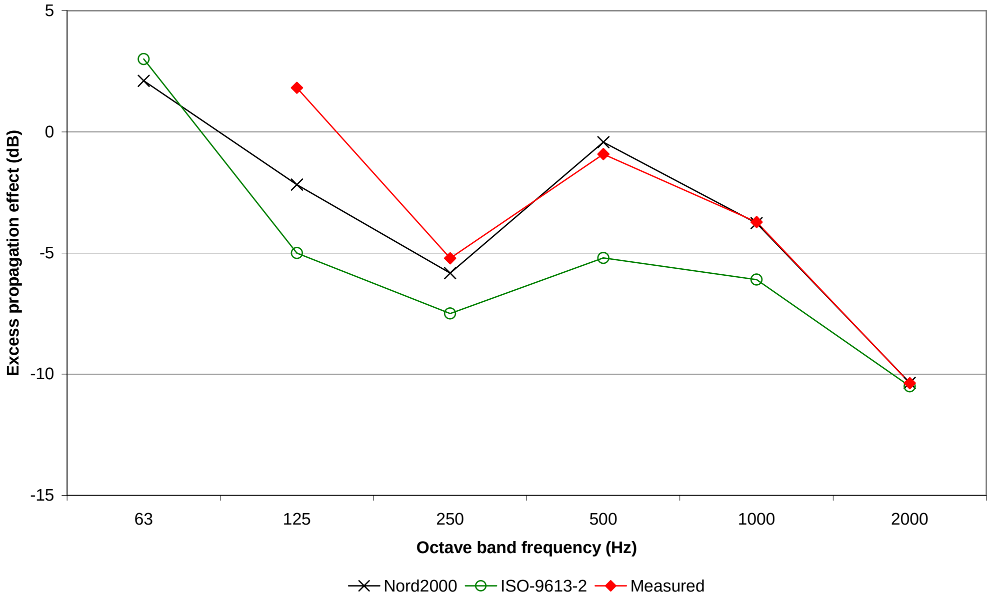

Figure 29
Excess propagation effect predicted by Nord2000 (X black), by ISO 9613-2 (○ green), and measured (♦ red). Downwind, distance 1500 m, source height 50 m, and receiver height 2 m.

9. Conclusion

The validation measurements for downwind propagation from a loudspeaker over flat grass-covered ground show a fine agreement between measurements and predictions by the Nord2000 method in the considered range of propagation distances (up to 1500 m). The average difference in A-weighted levels is 0.1 dB with a standard deviation of 0.7 dB which is very fine. Also, the agreement between measured and predicted spectra is good.

The validation measurements for upwind propagation from a loudspeaker over flat grass-covered ground show a less good but still acceptable agreement between measurements and predictions by the Nord2000 method considering the well-known problem of making accurate prediction in long-distance upwind cases. On average the predicted A-weighted noise levels are 4 dB higher than the measured levels with standard deviation of 1.9 dB. In principle, the Nord2000 method could be adjusted to give a better fit to the validation measurements, but it would be dubious to change the method based on only one experiment. Furthermore, noise levels in an acoustical shadow zone caused by upwind are in general low and very unstable. Therefore, it can be considered an advantage that the shadow zone effect predictions are conservative.

The validation measurements for downwind and upwind propagation from a loudspeaker over non-flat terrain show that predictions by Nord2000 is producing A-weighted noise levels, which on average are within 0.5 dB of the measured values with a standard deviation of 1.9 dB. This is considered a good agreement taking into account the complexity of the terrain and the meteorological conditions. In downwind Pos. 3 at a distance of approximately 1000 m the measured spectra show attenuation at high frequencies, which most likely are to the result of a moderate acoustical shadow zone normally seen during upwind propagation. The most likely explanation is that the effect is caused by a wind speed-up effect over the hill-shaped terrain. This is supported by the wind speed measurements showing a lower wind speed at the height 70 m than at 10 and 29 m. This complex situation is predicted well with Nord2000.

The validation measurements with a wind turbine as a source show good agreement with Nord2000 predictions as well. On the average the A-weighted levels are within 1 dB with a standard deviation of 2.3 dB. The spectra for the excess propagation effect are not showing the same agreement as for the loud speaker measurements. This can in part be due to measurement distance for the sound power level which is considerably larger than for the loudspeaker measurements, the lower noise emission of the wind turbine making intermittent background noise a parameter and possibly the fact that the source may in reality be a distributed source rather than a point source. It was tested whether a distributed source would give better agreement in the predictions but no significant change was seen in the results.

For the wind farm measurement a good agreement was seen for spectra as well as for the A-weighted levels. This validation is slightly different from the other parts as the results are given as noise levels rather than the excess propagation effect.

Generally the conclusion on validation is that for the tested situations Nord2000 shows a fine agreement with noise measurements for simple flat terrain with simple meteorology and for complex terrain with complex meteorology. When compared to ISO 9613-2 the Nord2000 model is an improvement especially for the complex situations.

10. References

[1] B. Plovsing and J. Kragh, *Nord2000. Validation of the Propagation Model,* DELTA Acoustics and Electronics, Report AV 1117/06, 2006.

[2] B. Plovsing and J. Kragh, *Nord2000. Comprehensive Outdoor Sound Propapagtion Model. Part 1: Propagation in an Atmosphere without Significant Refraction,* DELTA Acoustics & Vibration, Report AV 1849/00, 2001.

[3] B. Plovsing and J. Kragh, *Nord2000. Comprehensive Outdoor Sound Propapagtion Model. Part 2: Propagation in an Atmosphere with Refraction,* DELTA Acoustics & Vibration, Report AV 1851/00, 2001.

[4] J. Kragh and B. Plovsing, *Nordic Environmental Noise Prediction Methods, N2000 Summary Report,* DELTA Acoustics & Vibration, Report AV 1719/01, 2001.

[5] B. Plovsing, *Proposal for a Nordtest Method: Nord2000 – Prediction of Outdoor Sound Propagation*, DELTA Acoustics, Report AV 1106/07, 2007.

[6] B. Søndergaard, *Noise and Energy Optimization of wind farms - Loudspeaker measurements. Design of tests*, DELTA Acoustics, Technical Note AV 1242/09, 2009.

[7] IEC 61400-11:2002 edition 2.1 Wind turbine generator systems – Part 11: *Acoustic noise measurement techniques*.

Annex A - Approximation of the measured sound speed profile by the Nord2000 log-lin profile in the Høvsøre experiment

This annex contains a few examples where the effective sound speed profile measured at Høvsøre is compared to the Nord2000 log-lin profile.

Figure 30 shows a result from a wide signal sequence with duration 30 second where the measured sound speed profile are well modelled by the log-lin profile. The experience is that this will be the case if wind and temperature profiles are well fitted by the Businger-Dyer equations as shown in Figure 31 and Figure 32.

The general trend is that the longer the average time is the better is the fit. For the entire measurement period at Høvsøre the agreement between the wind and temperature profile and the Businger-Dyer equations is very good.

For short time periods like the single signal sequence time at Høvsøre fluctuations in wind and temperature profiles are seen. Figure 33 shows a case where the measured sound speed profile is less well modelled by the log-lin profile. In the present case the deviations are mainly caused by irregularities in the wind speed profile. However, the overall experience from the Høvøre experiment is that the prediction of excess propagation effects by Nord2000 is only slightly affected by such irregularities.

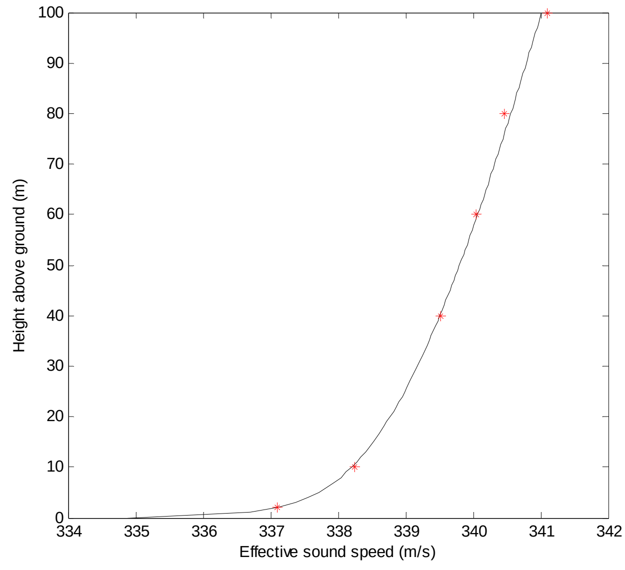

Figure 30
Agreement between measured sound speed profile and log-lin profile for wide-band signal sequence #5, duration 30 sec.

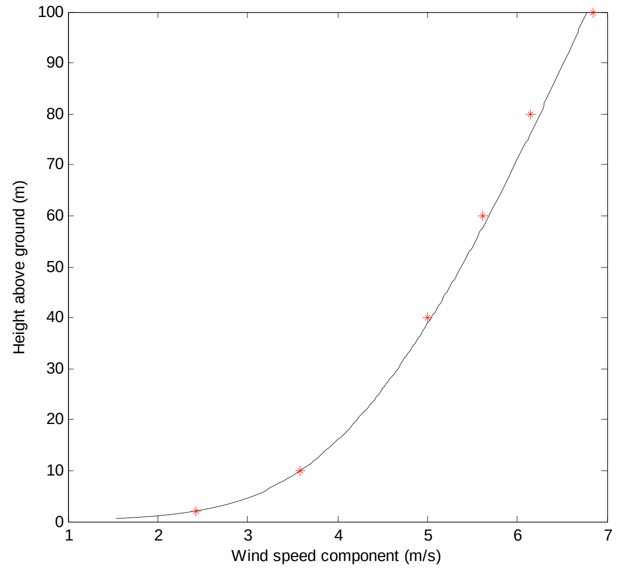

Figure 31
Agreement between measured wind speed profile and the Businger-Dyer equation for wide-band signal sequence #5.

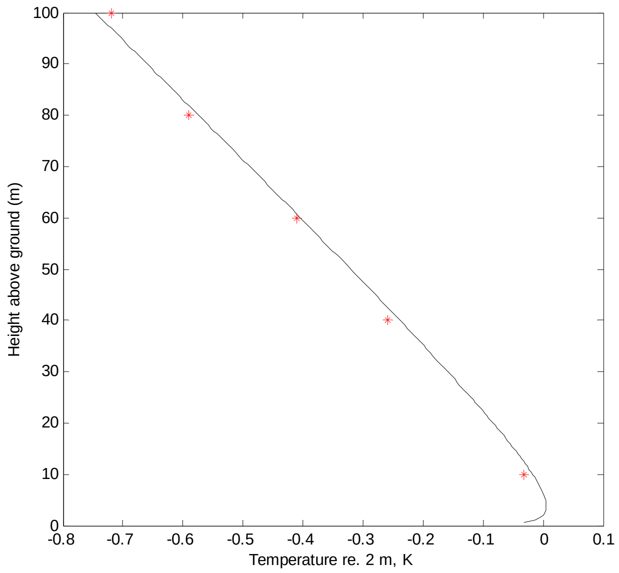

Figure 32
Agreement between measured temperature profile and the Businger-Dyer equation for wide-band signal sequence #5.

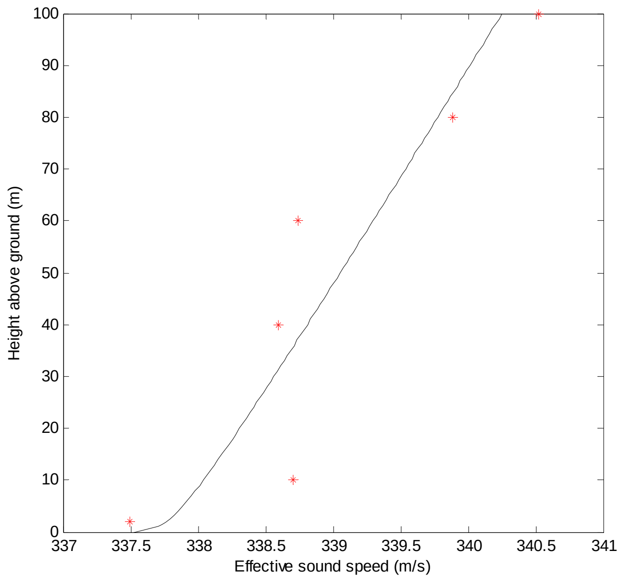

Figure 33
Agreement between measured sound speed profile and log-lin profile for wide-band signal sequence #7, duration 30 sec.

Annex B - Loudspeaker measurements at Høvsøre. Measured and predicted average spectra

This annex contains results from the Høvsøre loudspeaker experiment for all propagation cases. Subsection 10.1 and 10.2 contains the results for downwind and upwind propagation, respectively.

10.1 Downwind propagation

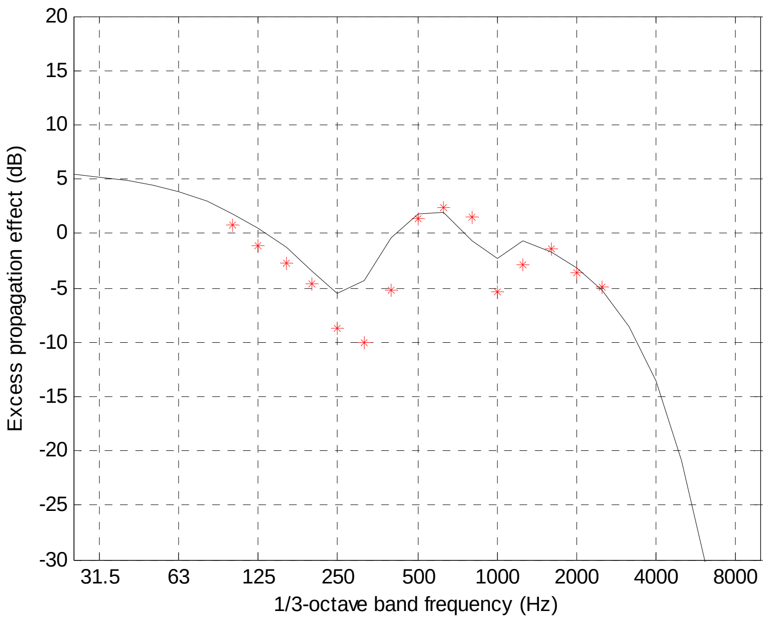

Figure 34
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 500 m, source height 30 m, and receiver height 2 m.

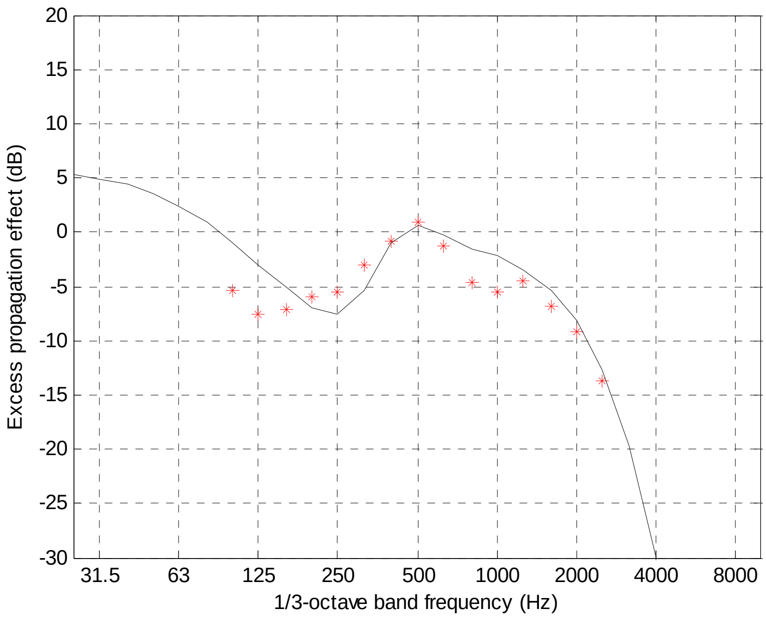

Figure 35
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1000 m, source height 30 m, and receiver height 2 m.

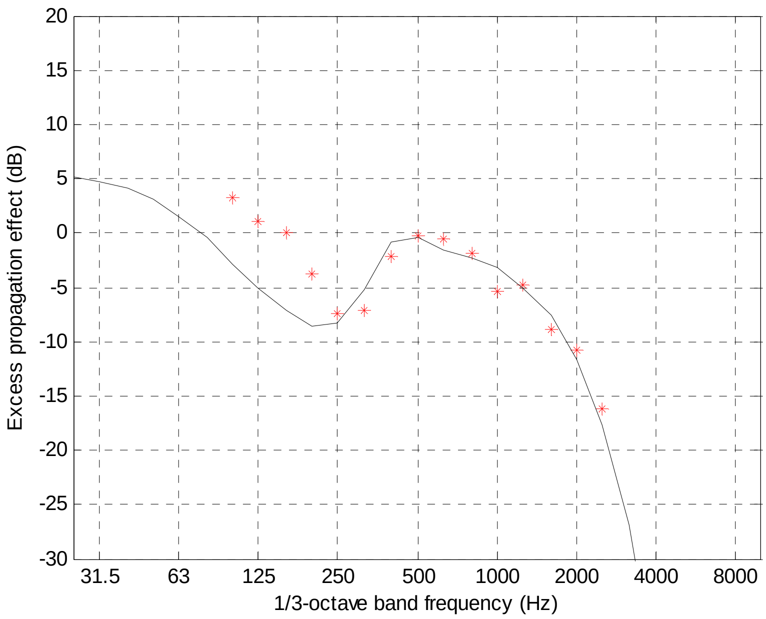

Figure 36
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1500 m, source height 30 m, and receiver height 2 m.

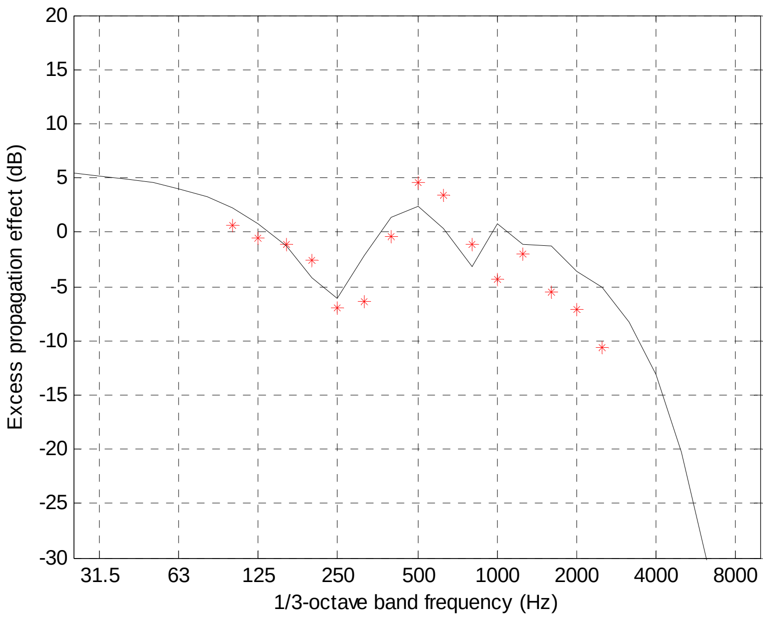

Figure 37
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 500 m, source height 50 m, and receiver height 2 m.

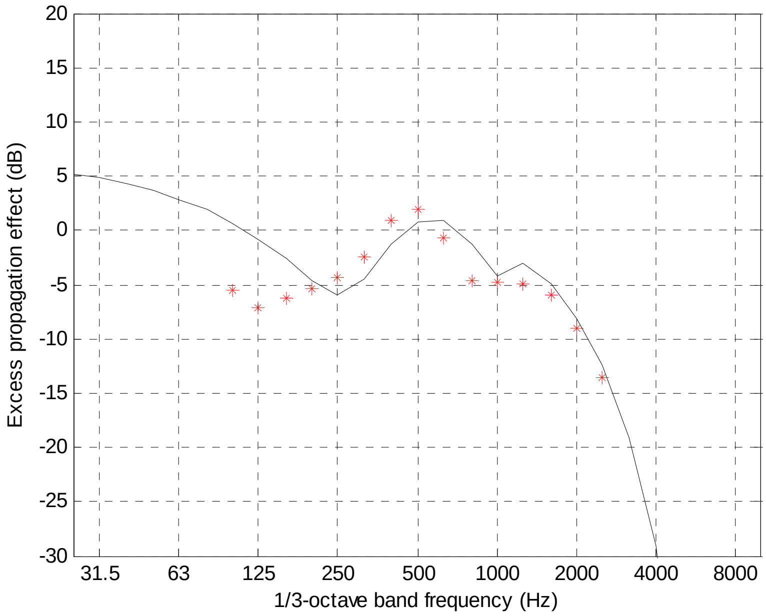

Figure 38
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1000 m, source height 50 m, and receiver height 2 m.

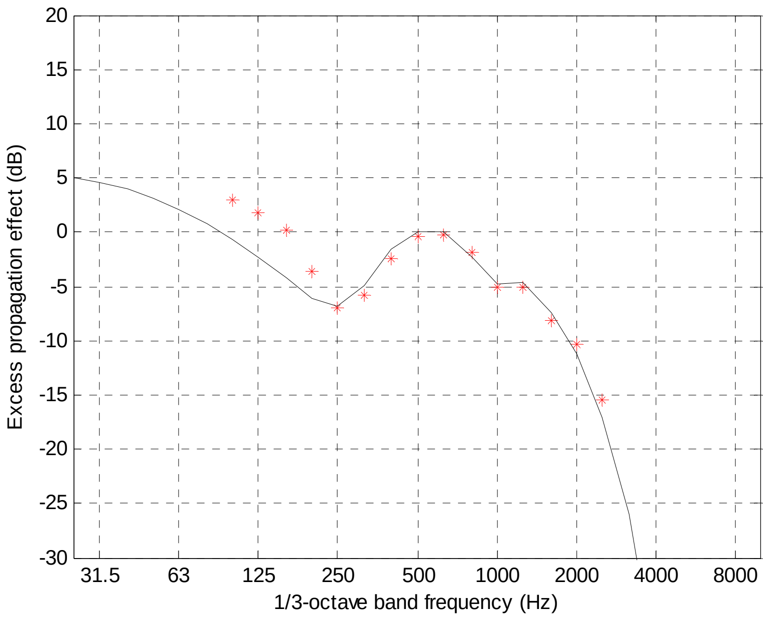

Figure 39
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1500 m, source height 50 m, and receiver height 2 m.

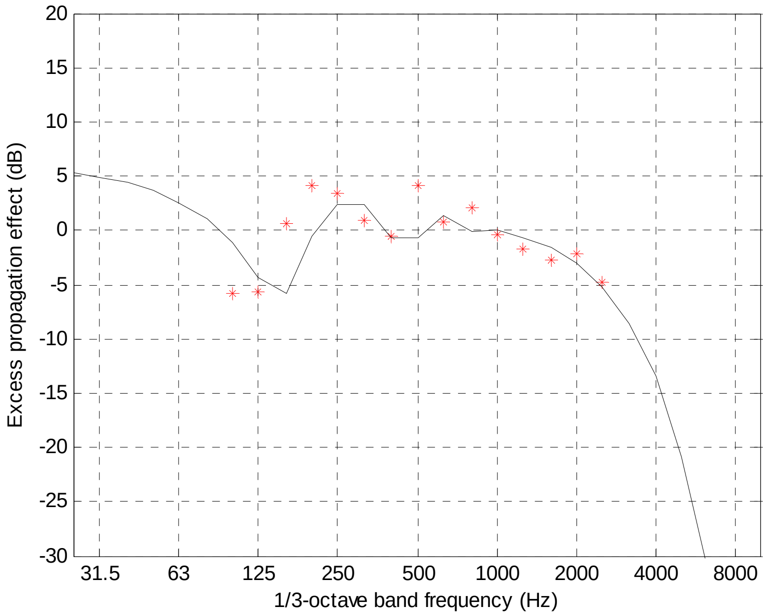

Figure 40
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 500 m, source height 30 m, and receiver height 5 m.

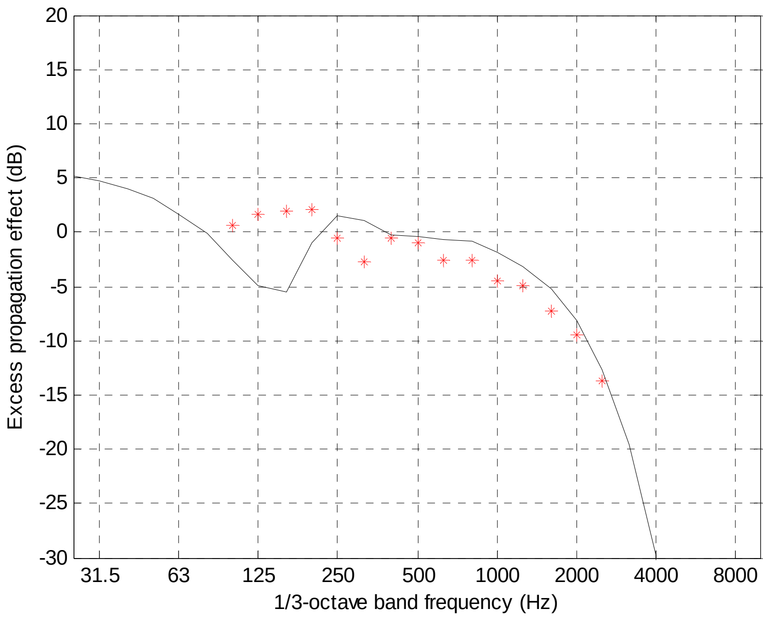

Figure 41
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1000 m, source height 30 m, and receiver height 5 m.

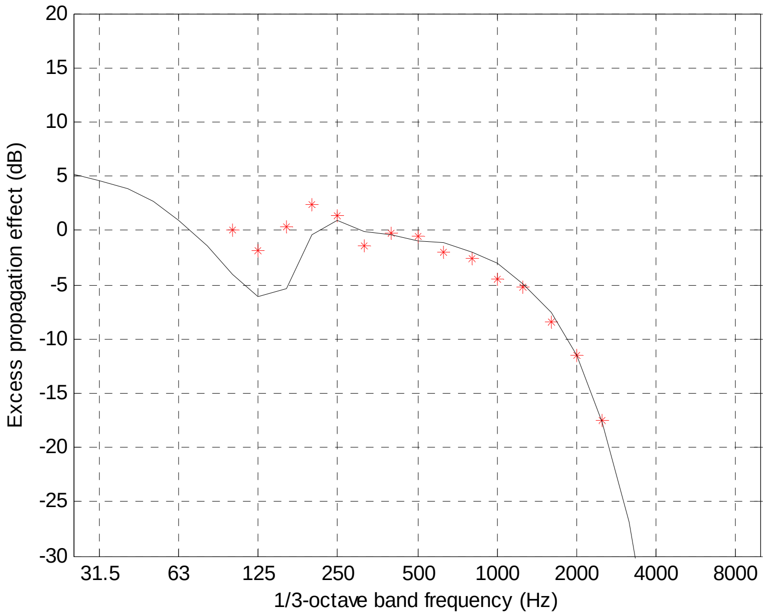

Figure 42
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1500 m, source height 30 m, and receiver height 5 m.

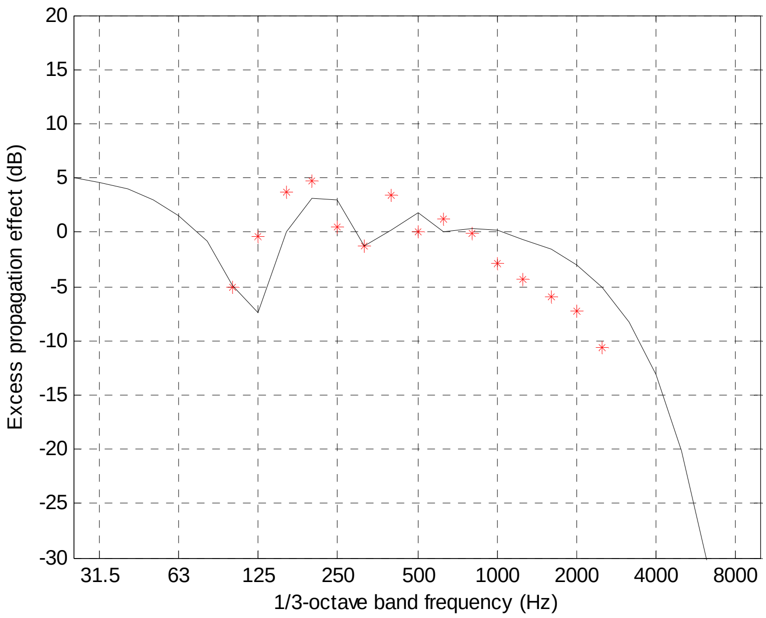

Figure 43
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 500 m, source height 50 m, and receiver height 5 m.

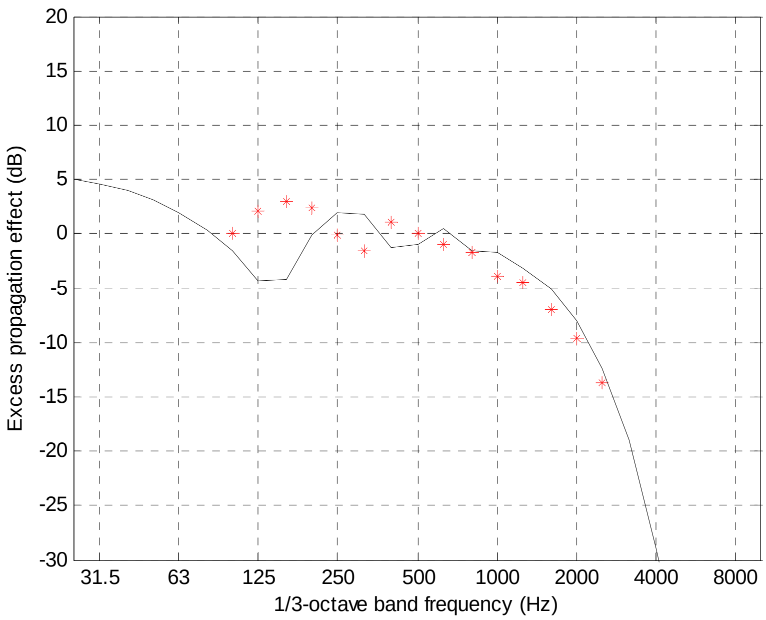

Figure 44
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1000 m, source height 50 m, and receiver height 5 m.

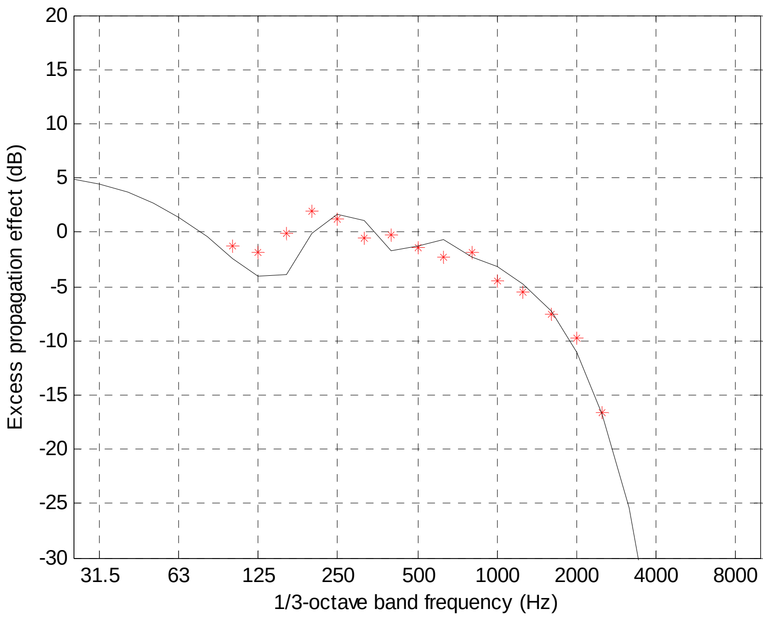

Figure 45
Measured (*) and predicted (line) excess propagation effect. Downwind, distance 1500 m, source height 50 m, and receiver height 5 m.

10.2 Upwind propagation

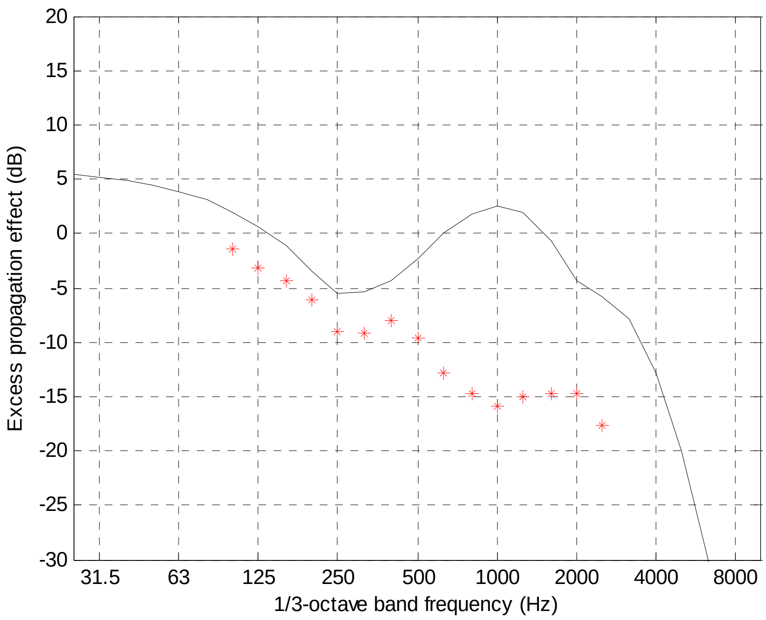

Figure 46
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 500 m, source height 30 m, and receiver height 2 m

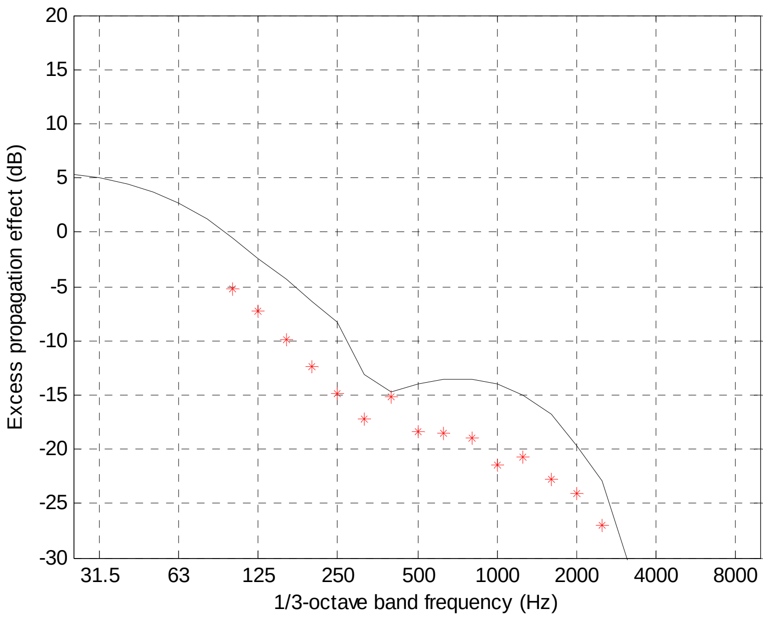

Figure 47
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 1000 m, source height 30 m, and receiver height 2 m.

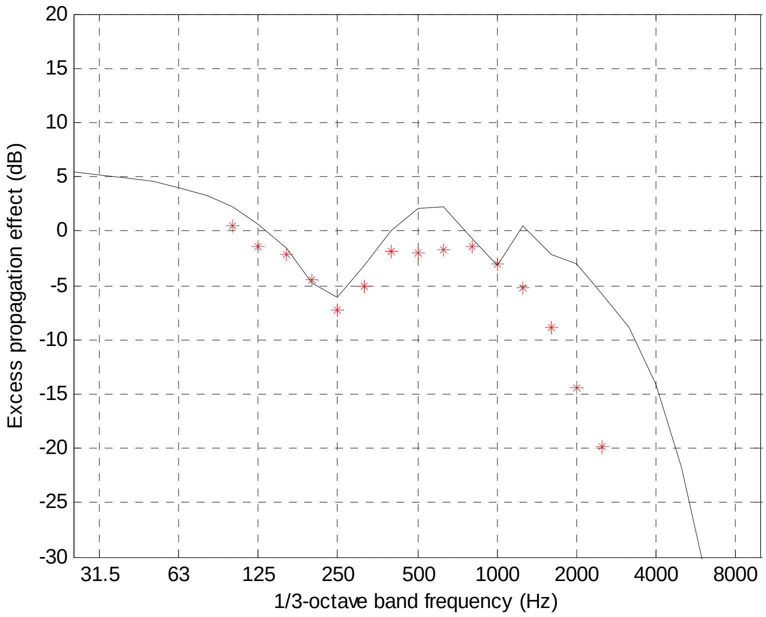

Figure 48
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 500 m, source height 50 m, and receiver height 2 m.

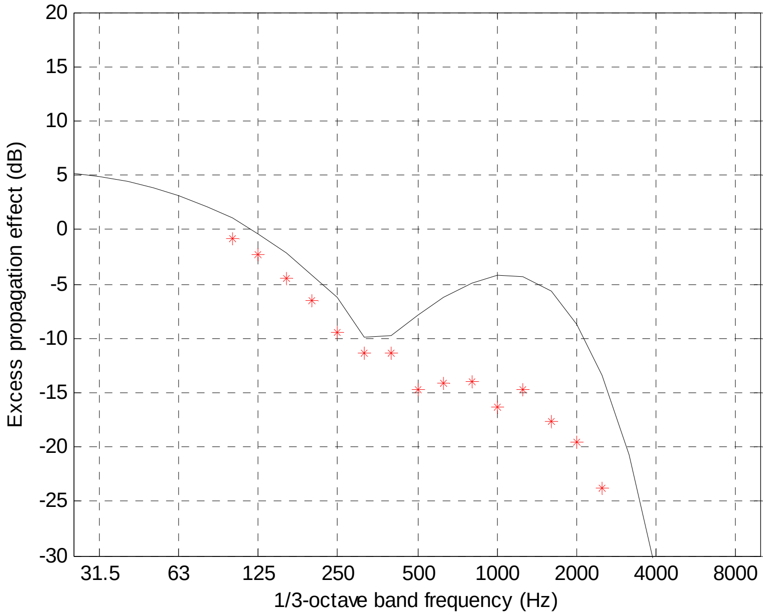

Figure 49
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 1000 m, source height 50 m, and receiver height 2 m.

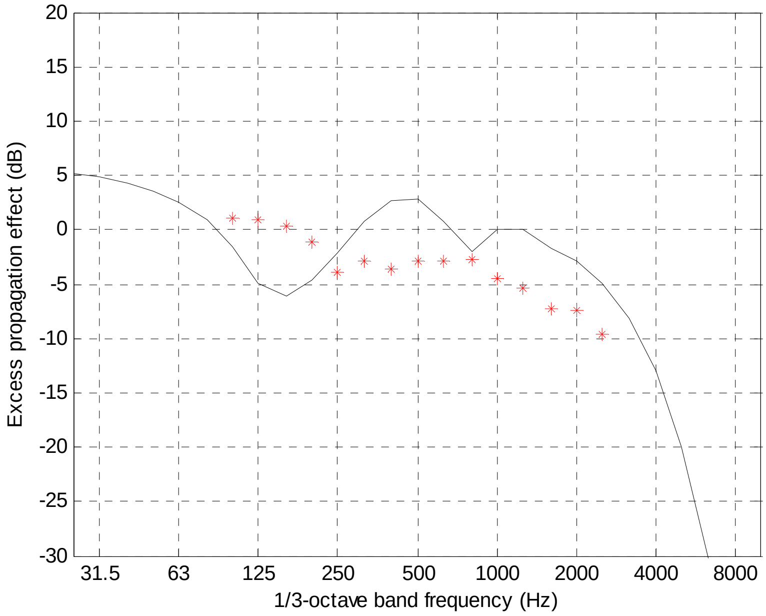

Figure 50
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 500 m, source height 30 m, and receiver height 5 m.

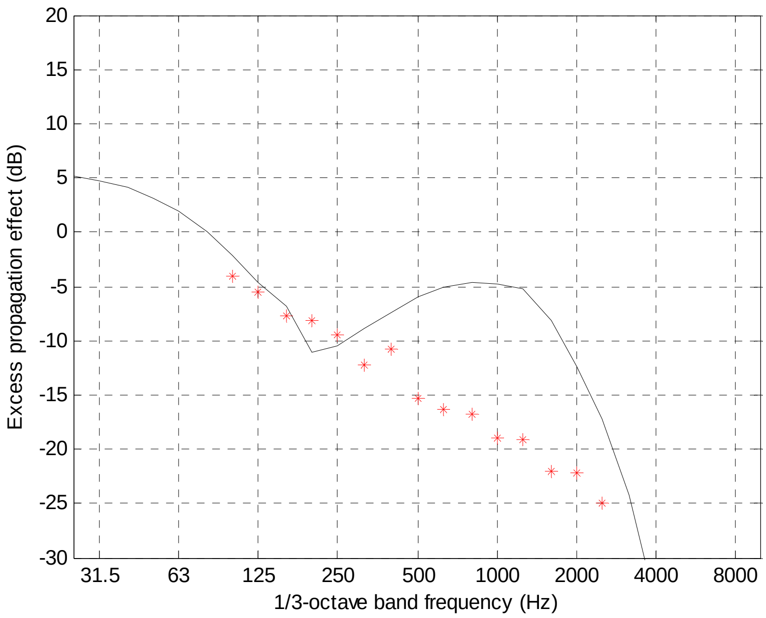

Figure 51
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 1000 m, source height 30 m, and receiver height 5 m.

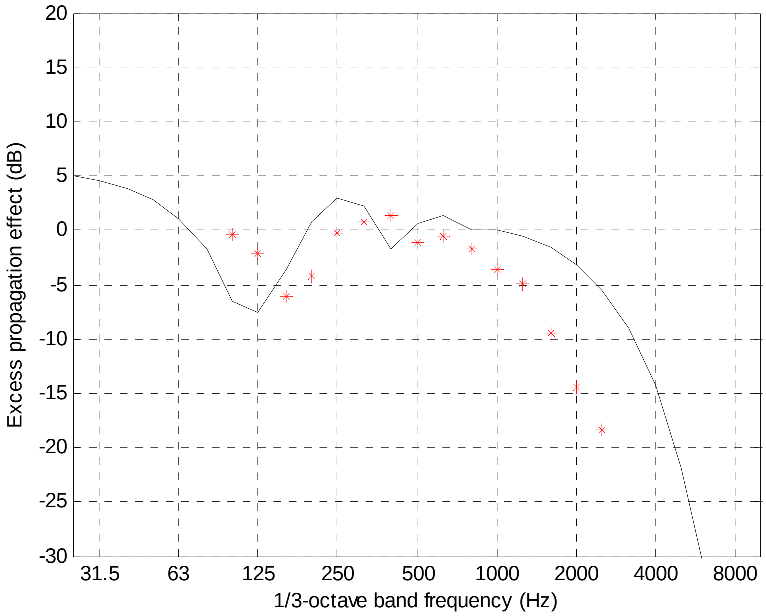

Figure 52
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 500 m, source height 50 m, and receiver height 5 m.

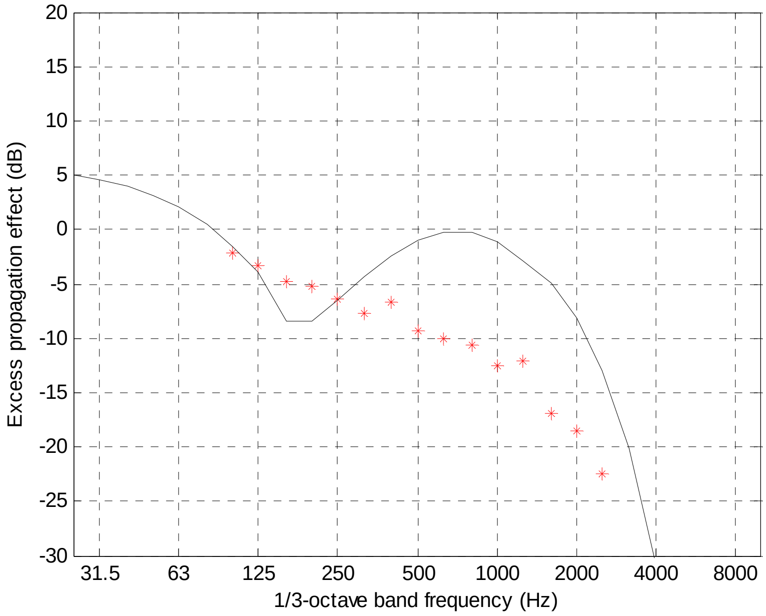

Figure 53
Measured (*) and predicted (line) excess propagation effect. Upwind, distance 1000 m, source height 50 m, and receiver height 5 m.

Annex C - Effective sound speed profiles observed in the Hitra loud-speaker experiment

Figure 54 to Figure 56 shows the estimated effective sound speed profile for each signal sequence during the measurement periods of following propagation cases:

- Downwind propagation, first measurement day (8 July)
- Downwind propagation, second measurement day (11 July)
- Upwind propagation, second measurement day (11 July)

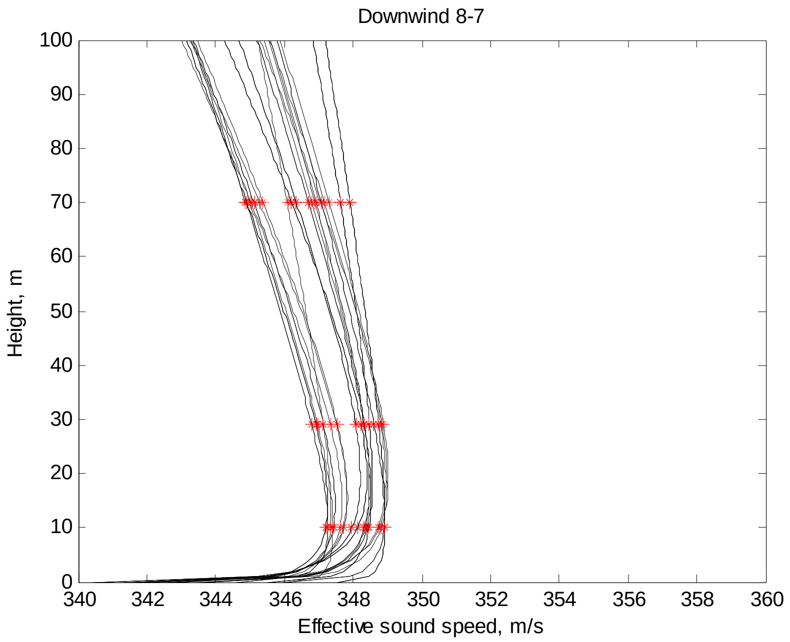

Figure 54
*Effective sound speed observed 10, 29, and 70 m above ground (red *) and the estimated sound speed profile (line) for each signal sequence during downwind measurements on the first measurement day (8 July).*

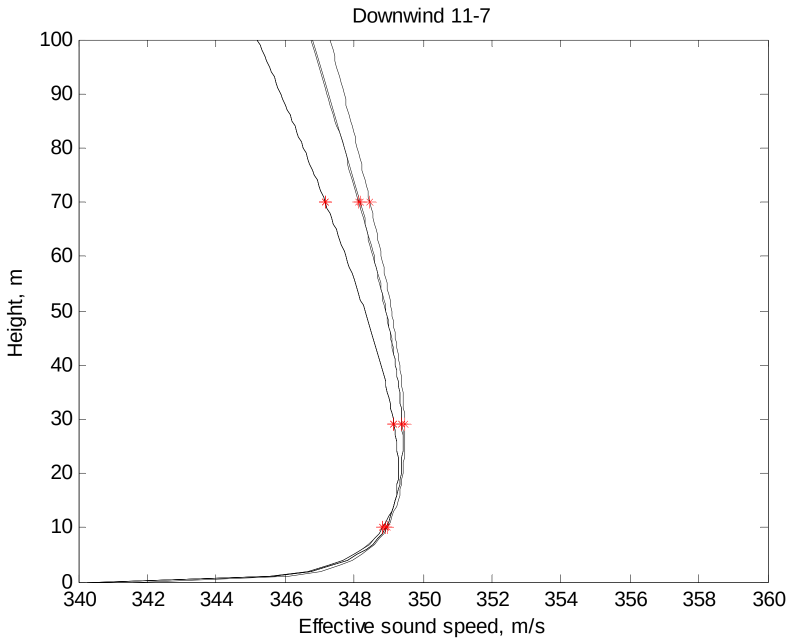

Figure 55
*Effective sound speed observed 10, 29, and 70 m above ground (red *) and estimated sound speed profile (line) for each signal sequence during downwind measurements on the second measurement day (11 July).*

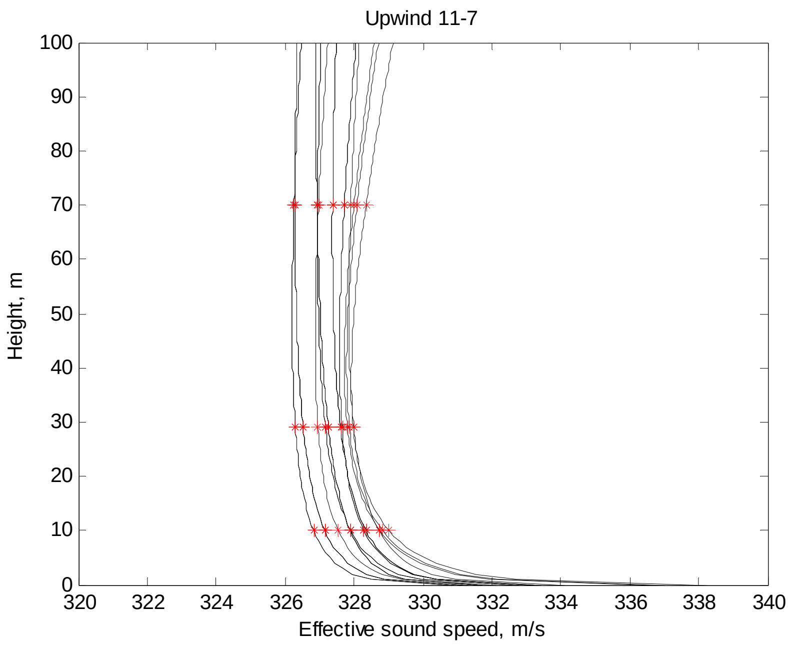

Figure 56
*Effective sound speed observed 10, 29, and 70 m above ground (red *) and estimated sound speed profile (line) for each signal sequence during upwind measurements on the second measurement day (11 July).*

Annex D - Loudspeaker measurements at Hitra. Measured and predicted average spectra

This annex contains results from the Hitra loudspeaker experiment for all propagation cases.

In measurement Pos. 1 (in both downwind and upwind propagation) the elevation angle of the loudspeaker seen from the measurement position was approximately 15°. From measurement in an anechoic chamber the directivity of the loudspeaker at this angle is known to be significant at high frequencies. Therefore, the measured excess ground effect result in Pos. 1 has been adjusted for the directivity pattern above 500 Hz according to Table 13. The values shown in Table 13 were estimated from measurements at 10° and 20° and particularly above 1 kHz where the adjustments are large this will increase the uncertainty at high frequencies in Pos. 1 considerably.

Frequency (Hz)	**Adjustment (dB)**
500	0.5
630	1.5
800	3
1000	5
1250	7
1600	9
2000	10
2500	11

Table 13
Correction of measured excess propagation effect for loudspeaker directivity.

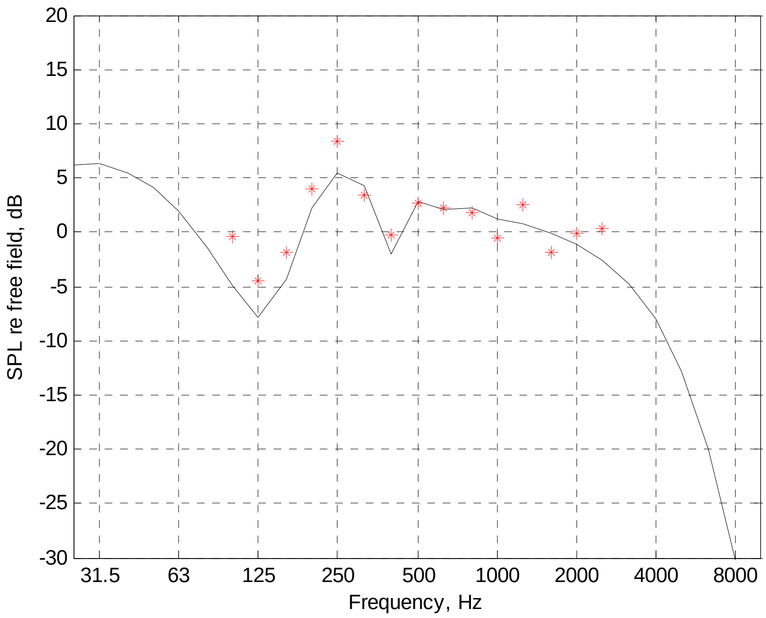

Figure 57
Downwind propagation, 8 July, Pos. 1, receiver height 2 m.

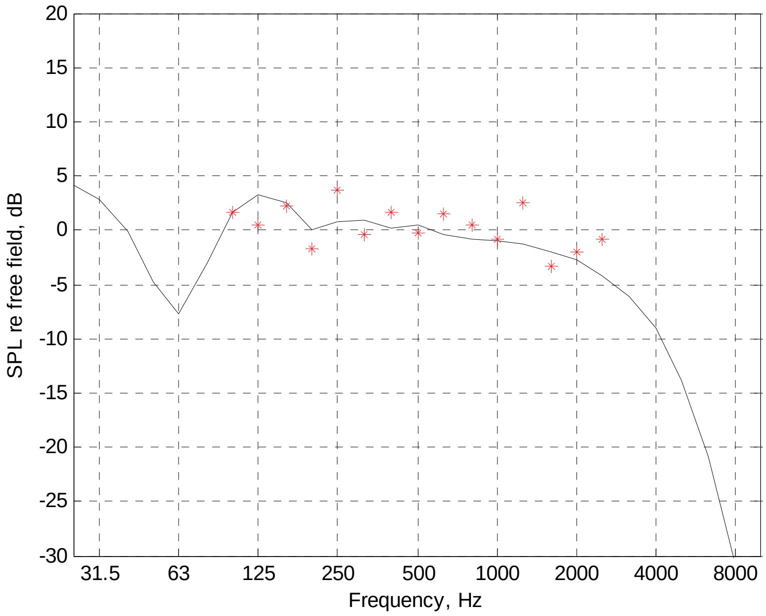

Figure 58
Downwind propagation, 8 July, Pos. 1, receiver height 5 m.

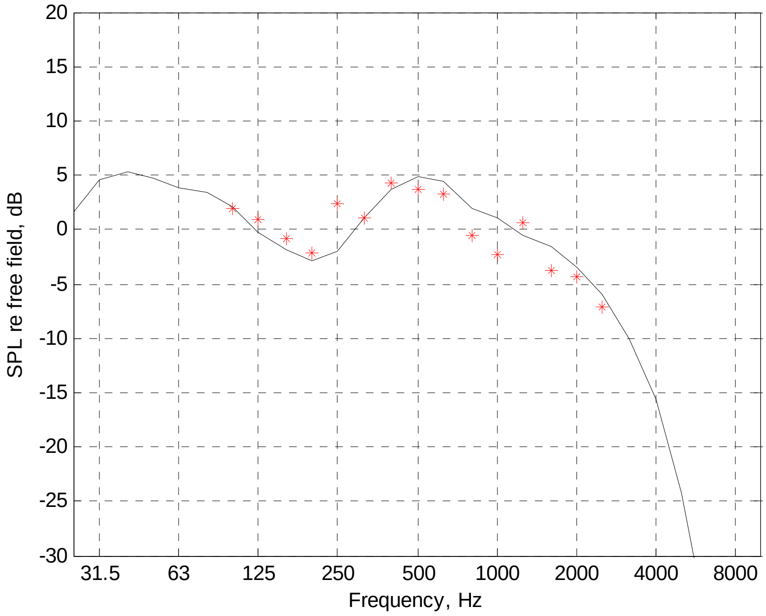

Figure 59
Downwind propagation, 8 July, Pos. 2, receiver height 2 m.

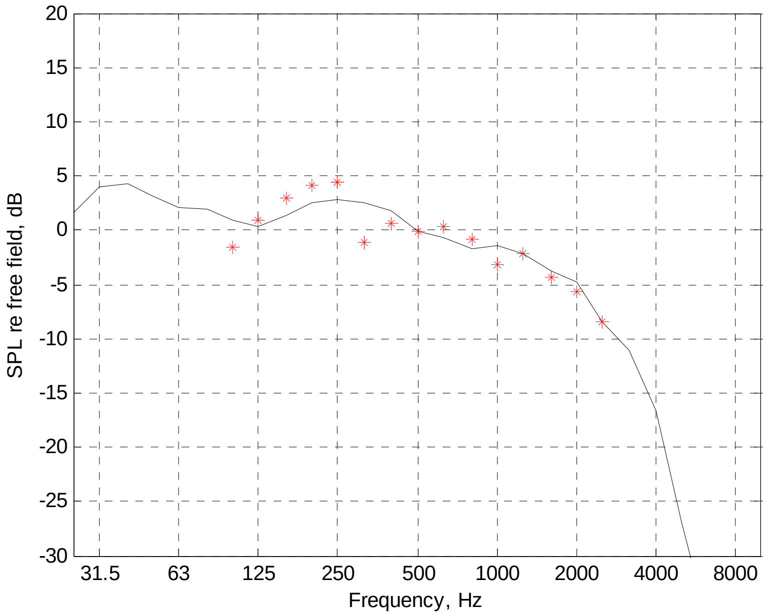

Figure 60
Downwind propagation, 8 July, Pos. 2, receiver height 5 m.

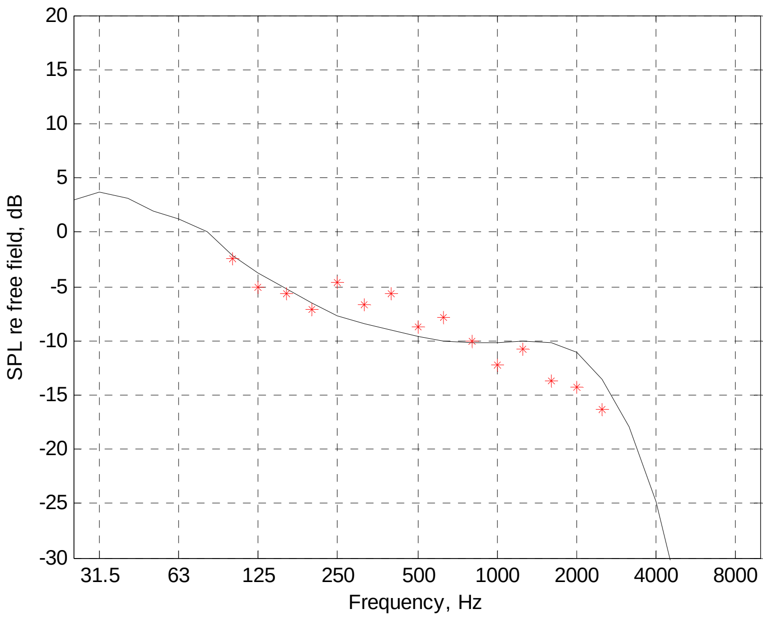

Figure 61
Downwind propagation, 8 July, Pos. 3, receiver height 2 m.

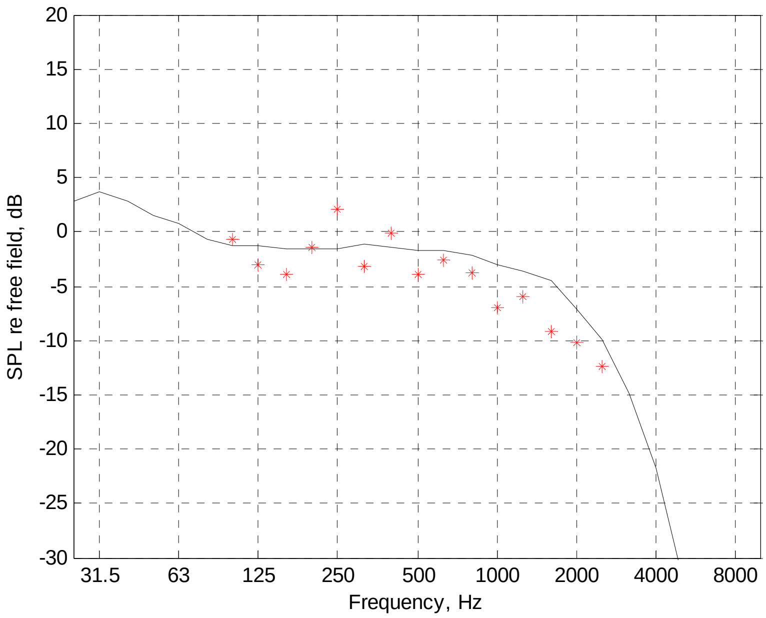

Figure 62
Downwind propagation, 8 July, Pos. 3, receiver height 5 m.

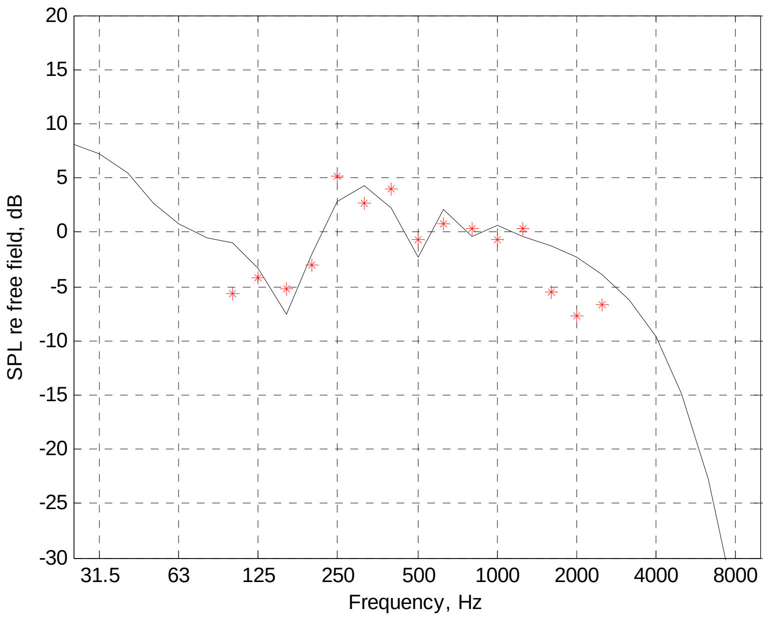

Figure 63
Upwind propagation, 11 July, Pos. 1, receiver height 2 m.

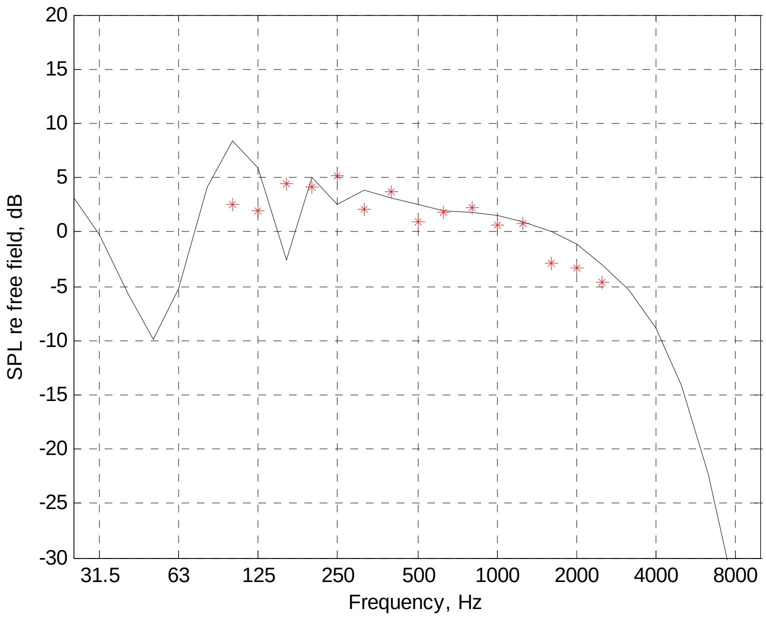

Figure 64
Upwind propagation, 11 July, Pos. 1, receiver height 5 m.

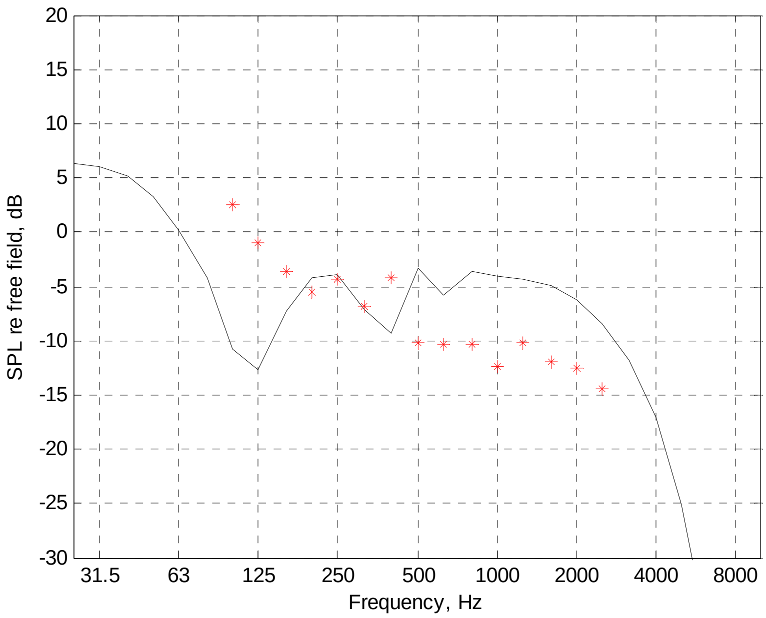

Figure 65
Upwind propagation, 11 July, Pos. 2, receiver height 2 m.

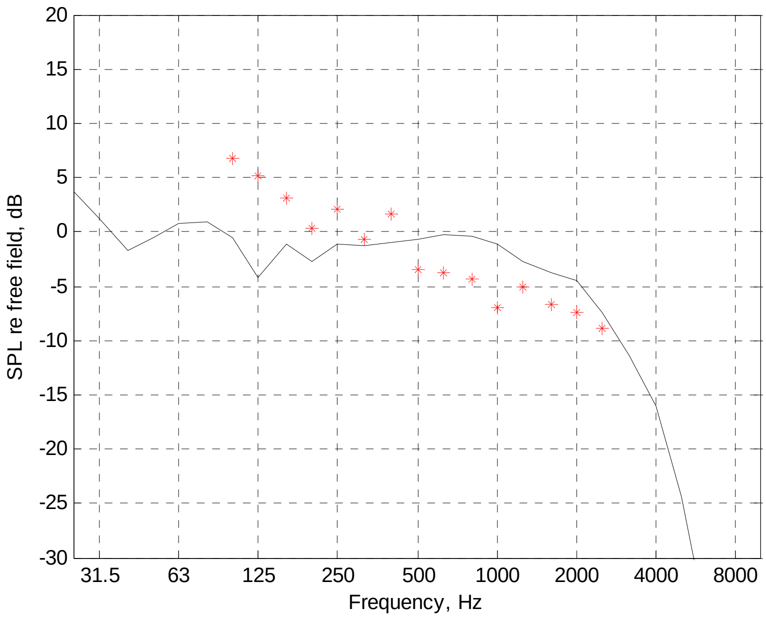

Figure 66
Upwind propagation, 11 July, Pos. 2, receiver height 5 m.

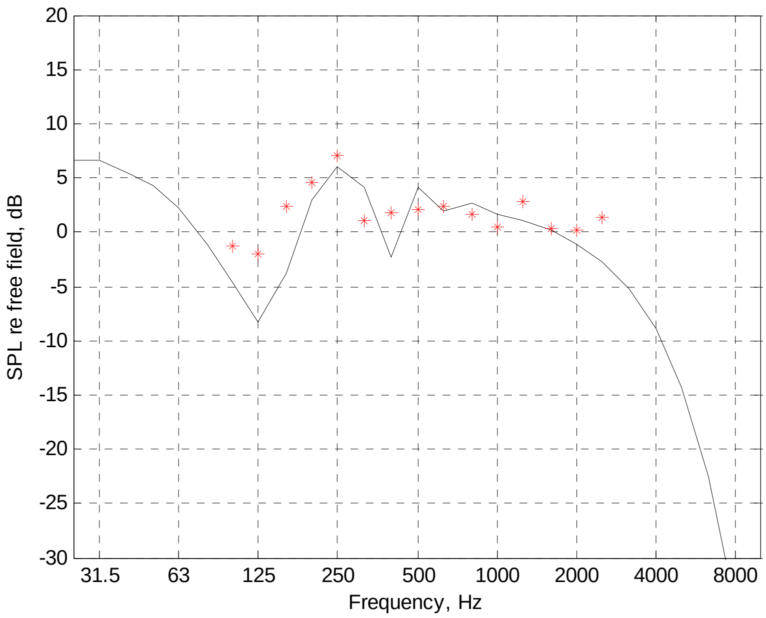

Figure 67
Downwind propagation, 11 July, Pos. 1, receiver height 2 m.

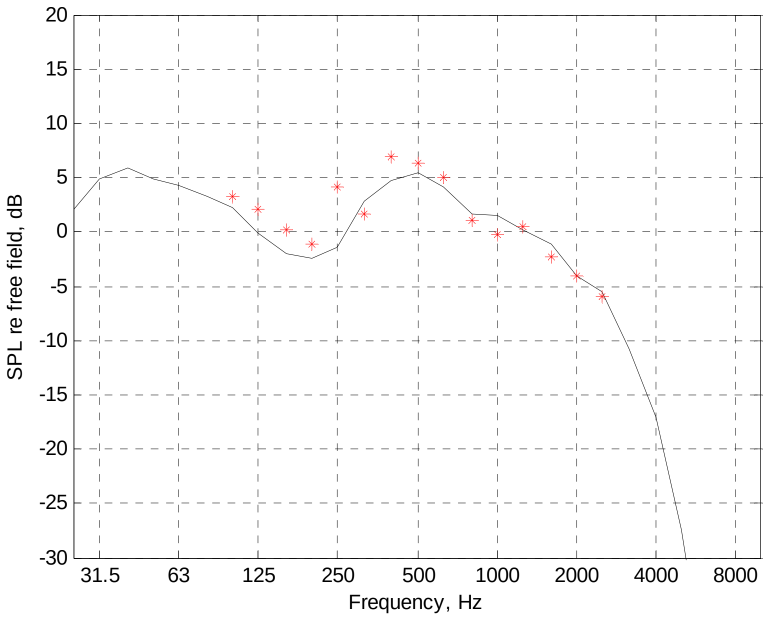

Figure 68
Downwind propagation, 11 July, Pos. 2, receiver height 2 m.