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Wind turbine noise prediction using Olive Tree Lab Terrain

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Summary

Calculation of noise propagation from wind turbines is complex, and large variations of sound immission levels are commonly observed at the same wind speed. These variations are influenced by sound emission (aerodynamic noise), but also by meteorological parameters such as temperature gradient, wind speed profile, wind direction, and turbulences. Commonly used models (ISO 9613-2 and Nord2000 for example) generally predict the average sound pressure levels adequately under downwind conditions, but often fail to predict noise levels in upwind conditions. In this paper we present the results of a collaborative research between SIXENSE Environment (ex SOLDATA Acoustic) and P.E Mediterranean Acoustics Research & Development (PEMARD), using on site experience on more than 350 French windfarms, and Olive Tree Lab - Suite v4.0 software which uses wave based geometrical acoustics to calculate sound propagation, including atmospheric refraction. The goal is to combine both approaches and introduce and test key parameters for wind turbine noise prediction. Calculation results are compared to long term noise & meteorological measurements. A good correlation is shown between calculation and measurements even in case of complex meteorological situations.

1. Introduction

Although models for outdoor sound propagation in a homogeneous atmosphere, where the speed of sound is constant, have been studied and developed extensively in the past decades the results are accurate only for short ranges of approximately under 200 m. At higher ranges the variation of the speed of sound due to wind and temperature stratification needs to be taken into account. Modelling the propagation of sound through such a non-homogeneous atmosphere is one of the most difficult tasks in outdoor acoustics due to the multiple physical phenomena that need to be accounted for such as turbulent scattering, creeping waves, caustics and many others (Attenborough, et al., 1995). A good historical review of sound propagation in moving media can be found in (Bateman, 1914) (Ostashev, 1997) (Piercy, Embleton, & Sutherland, 1977) and (Delany, 1977). Despite extensive research over the past decades there is no practical engineering model that can take into account all of the phenomena simultaneously.

This paper investigates the capabilities of Olive Tree Lab – Suite v4.0 (OTL-Suite), in performing long range sound propagation calculations. In general, OTL-Suite incorporates in its calculation engine, various types of models for the calculation of phenomena such as spherical wave reflection coefficients, multiple diffractions, atmospheric refraction and turbulence, and atmospheric absorption. The models used in the software engine are methodologies which provide accuracy and reasonable calculation times. In the case of refraction two separate models are being used, the model of (L'Espérance, Herzog, Daigle, & Nicolas, 1992) for downwind and upwind refraction and the model by (West, Walkden, & Sack, 1989) for shadow zone calculations, explained later on in this paper. OTL-Suite is a unique acoustic simulation software utilizing wave based geometrical acoustics (WBGA) (Lam, 2005) which preserve the wave nature of sound propagation. It is capable of modelling sound transmission in a non-homogenous atmosphere with linear sound speed profiles or by linear approximations of logarithmic sound speed profiles.

The paper begins with a brief historical review, followed by the theoretical model implemented by OTL-Suite. Subsequently benchmark cases results developed by (Attenborough, et al., 1995) and (WP2 Team, 2002) are compared to OTL-Suite calculation results, followed by a section where OTL-Suite calculation results are compared to measurements available for wind turbine noise. It is argued that a scatter plot of dB(A) values for a range of atmospheric parameters is a much better way to validate numerical models of long range sound propagation due to the dynamic nature of atmospheric conditions. Finally conclusions are presented.

2. A brief Historical Survey

A good historical review of sound propagation in moving media can be found in (Bateman, 1914) (Ostashev, 1997) (Delany, 1977) and (Piercy, Embleton, & Sutherland, 1977). In particular, the introduction in (Bateman, 1914) provides an excellent account of the early qualitative observations and mathematical formulations of the problem, while (Ostashev, 1997) has a detailed account of the investigations which occurred in the interwar period. What follows is a brief overview of the development of this field over the past decades.

Early modern analytical prediction schemes for atmospheric acoustics were developed during the early period after WWII. These schemes would approximate the sound speed with linear profiles and then graphically combine them for the cases of stratified mediums. The advantage of assuming a linear sound speed profile in a medium is that it allows for a closed form solution to the wave equation. The widespread adoption of the computer also led to the development of numerical algorithms which could tackle more general problems in ocean acoustics. Later in the 1980s these methods would also be implemented for the field of atmospheric acoustics.
One of these numerical methods was the Fast Field Program which was originally developed for underwater acoustics and was later implemented for atmospheric acoustics in the mid-1980s. The intention was to make the fastest possible algorithm that could carry out propagation predictions in real time. This method is capable of calculating the sound pressure of a monopole source above a flat ground and immersed in a layered atmosphere. Complicated wind and temperature profiles can be approximated by dividing the atmosphere into multiple horizontal layers with constant wind and temperature profiles. The FFP was originally designed as a two dimensional formulation for an axisymmetric atmosphere but was later generalized to three dimensions (Nijs & Wapenaar, 1990) (Wilson, 1993).

The Parabolic Equation method was applied to the field of ocean acoustics in the late 1970s and atmospheric acoustics in 1988 after being successfully used in such diverse fields as electromagnetic wave propagation, seismic waves, quantum mechanics and many others (Attenborough, et al., 1995). Whereas the Fast Field Program can only model horizontal layers of the homogenous atmosphere and homogenous grounds, the PE method is capable of modelling arbitrary terrains and atmospheric conditions including range-dependent phenomena such as turbulence. Two solutions are popular, the finite difference Crank-Nicholson Parabolic Equation method and the Green's Function Parabolic Equation method. The CNPE has been shown to be more accurate in situations with large sound speed gradients while the GFPE is more efficient. Like the FFP both of these methods were originally developed for a two dimensional axisymmetric atmosphere although a three dimensional GFPE method was later developed (Salomons E. M., 2001).

All the above numerical methods can be considered to be wave models and they successfully model arbitrary cases of inhomogeneous atmospheres and terrains. However they are still too computationally expensive to be used for practical engineering purposes. This is why there is an interest to expand the classical ray model from geometrical acoustics to deal with inhomogeneous mediums. Although the ray model is considered to be only a high frequency approximation of the wave model it does have the advantages that computational times tend to be faster while also providing an easy visual interpretation of wave propagation (Salomons E. M., 1994).

Rayleigh was the first to tackle the ray model for moving inhomogeneous mediums in his 1896 treatise. The model was further developed to be able to include phenomena such as caustics and range-dependent sound speed profiles. These models were still too complicated to implement for engineering purposes as the ray paths in an inhomogeneous medium need to be calculated numerically. It was in the early 1990s that a more practical model was proposed by (L'Espérance, Herzog, Daigle, & Nicolas, 1992). This model used the fact discussed by (Embleton, Thiessen, & Piercy, 1976) that the rays in downwind conditions are grouped in 4 rays for each order of reflection greater than 1. The model included the effects of turbulence, atmospheric absorption, geometrical spreading, the ground effect and refraction for linear sound speed profiles. Salomons developed a model to include logarithmic and power profiles (Salomons E. M., 1994) and also combined the ray model with theories of caustics (Salomons E. M., 1998).

In the case where the receiver is in the shadow zone in an upward sound propagation atmosphere and ray modelling fails to reach the receiver, the ray model can easily be combined with the residual method first treated by Pierce in his classic textbook (Pierce, 1994) and later implemented by many researchers who finally improved the method to be able to calculate the sound pressure level anywhere in the shadow zone (Berry & Daigle, 1988) (West, Walkden, & Sack, 1989). A limiting assumption of the residual series method is that it assumes a linear sound speed profile. The above methods do not take into account the effect of turbulence scattering sound into the shadow zone, a phenomenon that increases the SPL in the high frequencies considerably (Salomons E. M., 2001). A more recent paper presents an alternative analytical solution that includes turbulent scattering in the shadow zone (Lam, 2009).

Starting in the late 1990’s these models were eventually implemented in engineering prediction schemes. Between 1996 and 2000 DELTA developed the Nord2000 prediction scheme which was capable of predicting various industrial noise sources and included the heuristic model by (L'Espérance, Herzog, Daigle, & Nicolas, 1992) although it only implemented a single bounce version of the model (Attenborough, Li, & Horoshenkov, 2007) (Plovsing, B; Kragh, J, 2006) (Plovsing, B; Kragh, J, 2006). Harmonoise, a European project, was developed in 2002 to offer a state of the art prediction scheme for which other prediction schemes could base themselves on. The Harmonoise scheme also has an improved method for linearly approximating a logarithmic sound speed profile which was later also implemented in the Nord2000 prediction scheme (Salomons, Maercke, Defrance, & deRoo, 2011) (Plovsing, B; Kragh, J, 2006).

3. Theoretical Background

What follows is a brief description of the models used by OTL-Suite. Further details can be found in the references cited.

3.1 Theory of the propagation of sound in a non-homogenous atmosphere inside the bright zone

For cases of downward or upward refraction OTL-Suite implements the heuristic model originally developed by (L'Espérance, Herzog, Daigle, & Nicolas, 1992). The advantage of the model is that it is simple to implement and takes into account multiple bounces of rays in cases of strong downward refraction instead of just the two rays of the single bounce model. The model does this by taking advantage of the fact that in the case of a positive gradient there is one direct path, three paths with one order of reflection and four paths for each successive order of reflection. Thus the intersection points of each path with the ground can be found by finding the roots of a fourth order polynomial equation for each reflection order.

Once the rays are found their path lengths and times are calculated using geometrical parameters described in the original paper. The model also takes into account atmospheric absorption and turbulence.

3.2 Theory of propagation of sound in the shadow zone

The heuristic model predicts that in cases of negative sound speed gradients and where the receiver is located in a shadow zone, no rays will reach the receiver and the sound pressure level will be 0. In reality there is a creeping wave which propagates above the ground and diffracts acoustical energy into the shadow zone (Pierce, 1994). In order to predict the sound pressure level in the shadow zone, OTL-Suite combines the heuristic model with a residual method outlined in (West, Walkden, & Sack, 1989). This involves expressing a Z-dependent Green's function in a residual form whose solutions are Airy functions. The pressure at the receiver is then calculated using the Hankel function.

3.3 Approximating a logarithmic sound speed profile with a linear sound speed profile

The input parameters required to model a logarithmic sound speed profile in OTL-Suite are: the Temperature at ground level (T), the temperature at a height z defined by the user, the wind speed $u(z_u)$ at a height z_u, the roughness constant (z_0) and the wind direction (φ) defined in OTL-Suite as the clockwise angle from the North with the downwind condition blowing from south to north. Figure 1 below shows how these parameters are entered in OTL-Suite.

In cases of a logarithmic sound speed profile the sound speed is described with the following equation:

$$c(z) = A\ln\left(\frac{z}{z_0} + 1\right) + Bz + c_0$$

Where A and B are given by:

$$A = \frac{u(z_u)\cos\theta}{\ln\left(\frac{z_u}{z_0}+1\right)} \qquad B = \frac{dT}{dz}\frac{10.025}{\sqrt{T+273.15}}$$

This time θ is the wind direction relative to the propagation of sound between the source and receiver and $\frac{dT}{dz}$ is the linear temperature gradient.

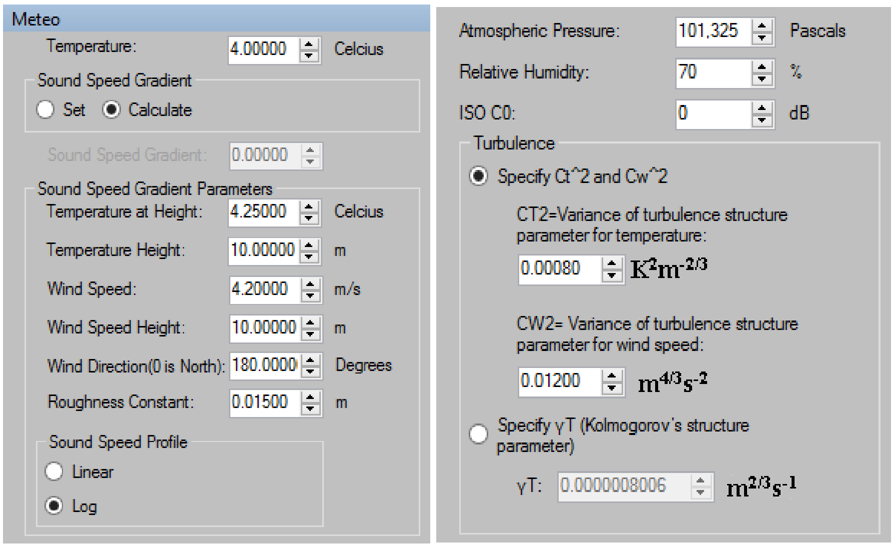

Figure 1: Screenshot of the Meteo side panel in OTL-Suite used for inputting atmospheric parameters for the modelling of atmospheric refraction, turbulence and absorption. These particular parameters were used for DELTA Cases 3 and 4 described in Section 6.

Since both the heuristic model and the residual method need to approximate any general sound speed profile with a linear profile, OTL-Suite employs the method by Harmonoise to approximate a logarithmic profile (Plovsing, B; Kragh, J, 2006). This involves finding the radius of curvatures of the logarithmic (A) and the linear (B) parts of the profile and combining them as follows:

$$r_{A,B} = \frac{1}{\frac{1}{r_A} + \frac{1}{r_B}}$$

Where

$$r_A = sign(A)\frac{R}{8}\sqrt{\frac{2\pi c_0}{|A|}} \qquad r_B = sign(B)\sqrt{\left(\frac{c_0}{|B|}\right)^2 + \left(\frac{R}{2}\right)^2}$$

The effective linear sound speed gradient can then be found using:

$$a = \frac{1}{r_{A,B}\cos\varphi}$$

Where φ is given by:

$$\varphi = \sin^{-1}\left(\frac{\sqrt{R^2 + (z_r - z_s)^2}}{2r_{A,B}}\right) + \tan^{-1}\left(\frac{z_r - z_s}{R}\right)$$

R is the horizontal range between the source and receiver while z_s and z_r are the source and receiver heights respectively.

4. Outline of Benchmark Cases

For the present study the results of OTL-Suite were compared against the benchmarks cases in (Attenborough, et al., 1995) which we will refer to as the 1995 benchmark cases, and some of the benchmark cases in (WP2 Team, 2002) which we will refer to as the Harmonoise benchmark cases. The 1995 benchmark cases include analytical solutions for linear sound speed profiles but they are only done for monochromatic frequencies. The Harmonoise benchmarks cases are done in a 1/3 Octave frequency resolution and include comparisons to the modern engineering prediction scheme Nord2000. They also include logarithmic sound speed profiles thus allowing us to test the capabilities of OTL-Suite in linearly approximating logarithmic sound speed profiles.

What follows is an outline of the benchmark cases used.

4.1 1995 Benchmark Cases

The 1995 benchmark cases consist of four cases corresponding to different atmospheres: a homogenous atmosphere with uniform sound speed (Case 1), a non-homogenous atmosphere with a strong positive linear sound speed gradient of 0.1 (Case 2), a non-homogenous atmosphere with a strong negative linear sound speed gradient of -0.1 (Case 3) and a composite sound speed profile (Case 4) which was not used as it exceeds the capabilities of OTL-Suite. Full details and descriptions of the cases can be found in (Attenborough, et al., 1995). In the original study only the analytical, FFP and PE methods of all the cases were presented.

The intention of the original paper was to develop benchmark cases of extreme atmospheric conditions but without the inclusion of effects such as turbulence, rough ground or uneven terrain. This would allow simple versions of new numerical methods to be tested against these benchmarks before being expanded to include other physical phenomena.

In the three cases considered calculations were performed for Source-Receiver ranges of up to 10000 m. The calculations were performed for three monochromatic frequencies: 10, 100 and 1000 Hz. Here we present the results for Case 2 and Case 3 at a range of 10000 m and a frequency of 100 Hz. The receivers were separated by 25 m.

The ground impedance was described using the Delany and Bazley 1 parameter model with a Flow resistivity of 205000 Pa s m^{-2} as opposed to the 4-parameter model used in the benchmark paper. The parameters used in the model are summarised in **Erreur ! Source du renvoi introuvable.**.

Table 1: Parameters used for 1995 Benchmark Cases

Parameter	Value
Density of air (ρ_0)	1.205 kg/m^3
Atmospheric Pressure	1 atm
Relative Humidity (RH)	70 %
Temperature (T_0)	22 ^{o}C
Ground Flow Resistivity (σ) (D&B)	205000 Pa s m^{-2}
Source Height (h_s)	5 m
Receiver Height (h_r)	1 m
Range (R)	10000 m
Frequency (f)	100 Hz

4.2 Harmonoise Benchmark Cases

OTL-Suite was compared against Case 1.1 of the Harmonoise benchmark cases. This case consists of a flat ground with uniform impedance for different Source-Receiver heights and Ranges. In total there are 144 different subcases. The atmospheric conditions used in the particular subcases under investigation are summarized **Table 2** below:

Table 2: Atmospheric conditions used in the Harmonoise Benchmark subcases

Index m	Atmospheric condition	Sound speed profile
m = 2	Linear sound speed Profile, no turbulence	$a = 0.05\ s^{-1}$, $c(z) = c_0 + az$
m = 3	Logarithmic sound speed profile, no turbulence	$b = 1\ ms^{-1}$, $c(z) = c_0 + b\ln(1+z/z_0)$
m = 5	Logarithmic sound speed profile, no turbulence	$b = -1\ ms^{-1}$, $c(z) = c_0 + b\ln(1+z/z_0)$

Due to the large number of subcases in case 1.1 the subcases were narrowed down to the ones consisting of a non-homogenous atmosphere, the ones that did not include atmospheric turbulence (thus the ones which have an index m = 2, 3 and 5), the subcases consisting of a locally reacting ground (grass), a range of 2000 m and a source/receiver height combination of $h_s = 0.5$ m with $h_r = 1.5$ m and $h_s = 5$ m with $h_r = 4$ m. These particular source/receiver height combinations were chosen to test the linear approximation of a logarithmic profile when the sources and receivers are close to the ground and far from the ground.

Thus the list of subcases considered are: C11_2132m and C11_3232m where the index m corresponds to the atmospheric conditions m = 2, 3 and 5. The parameters used for all the subcases are outlined in **Table 3** below:

Table 3: Modelling Parameters used in the Harmonoise Benchmark Cases

Parameter	C11_21322	C11_21323	C11_21325	C11_32322	C11_32323	C11_32325
Source height (m)	0.5	0.5	0.5	5	5	5
Receiver height (m)	1.5	1.5	1.5	4	4	4
Range (m)	2000	2000	2000	2000	2000	2000
Speed of sound (ms^{-1})	340	340	340	340	340	340
Roughness constant (m)	0.1	0.1	0.1	0.1	0.1	0.1
Ground Flow Resistivity (Pa s m^{-2})	200000 (Grass)	200000 (Grass)	200000 (Grass)	200000 (Grass)	200000 (Grass)	200000 (Grass)

OTL-Suite is compared to Basic and Engineering models, which are given below with their acronyms. The Basic models are, the Crank-Nicholson Parabolic Equation method (CPE TNO), the Green's Function Parabolic Equation method (GPE CST), the Fast Field Program (FFP CST) and for the subcases with a linear sound speed profile the Meteo-BEM (MBE CST) model. The engineering models, are the Nord2000 propagation model (N20 DEL) and the CRAYL model (CRA DEL). The distinction between Basic and Engineering models was made in (WP2 Team, 2002) and it applies to the rest of the paper. More details of these models can be found in (WP2 Team, 2002).

5. Results

5.1 1995 Benchmark Cases

Good agreement was found between OTL-Suite and the FFP, PE and analytical solutions used in the 1995 Benchmark Cases. In Case 2, the downward refracting atmosphere, OTL-Suite follows the trend quite well although the minima and maxima are significantly sharper than the 1995 Attenborough Case, especially at large ranges. Nevertheless in a more realistic scenario these minima and maxima would most likely be smoothed out by turbulence. In Case 3 there is a discontinuity present at a range of about 400 m indicating that the receiver is now in the shadow zone where the Transmission Loss drops sharply. Figure 5 in section 6.2 shows some of the sound ray paths from the source to receivers located at a range of 5000-7000 m.

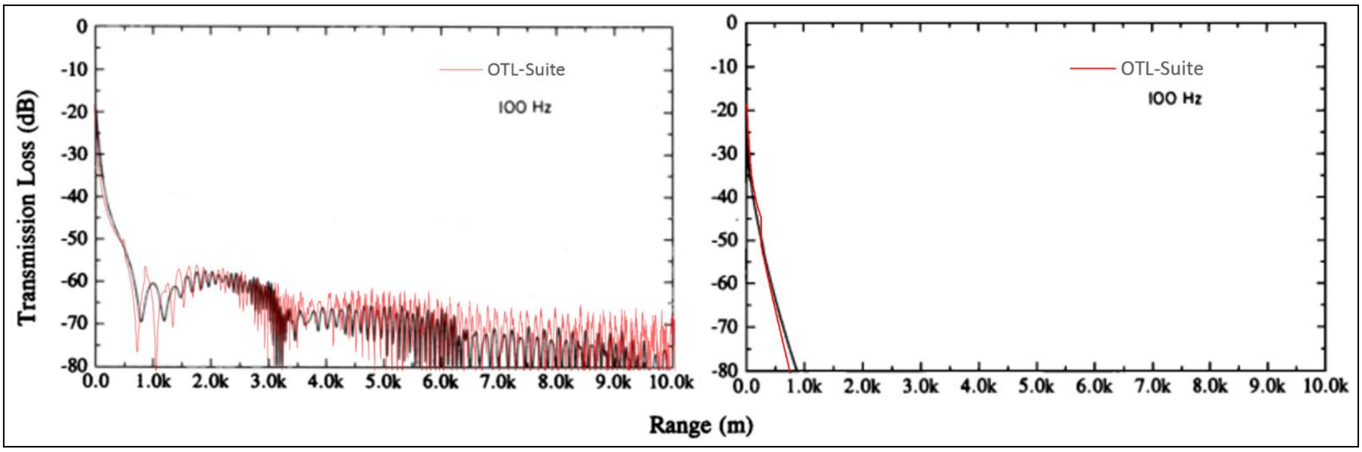

Figure 2: Comparison between OTL-Suite calculations (red line) and 1995 Benchmark Cases (black line). Left graph is for the case of a strong positive linear sound speed gradient of 0.1 s^{-1} while the right graph is for the case of a strong negative sound speed gradient of -0.1 s^{-1}. Both curves show transmission loss vs distance at 100Hz. Calculated graphs are superimposed on published data.

5.2 Harmonoise Benchmark Cases

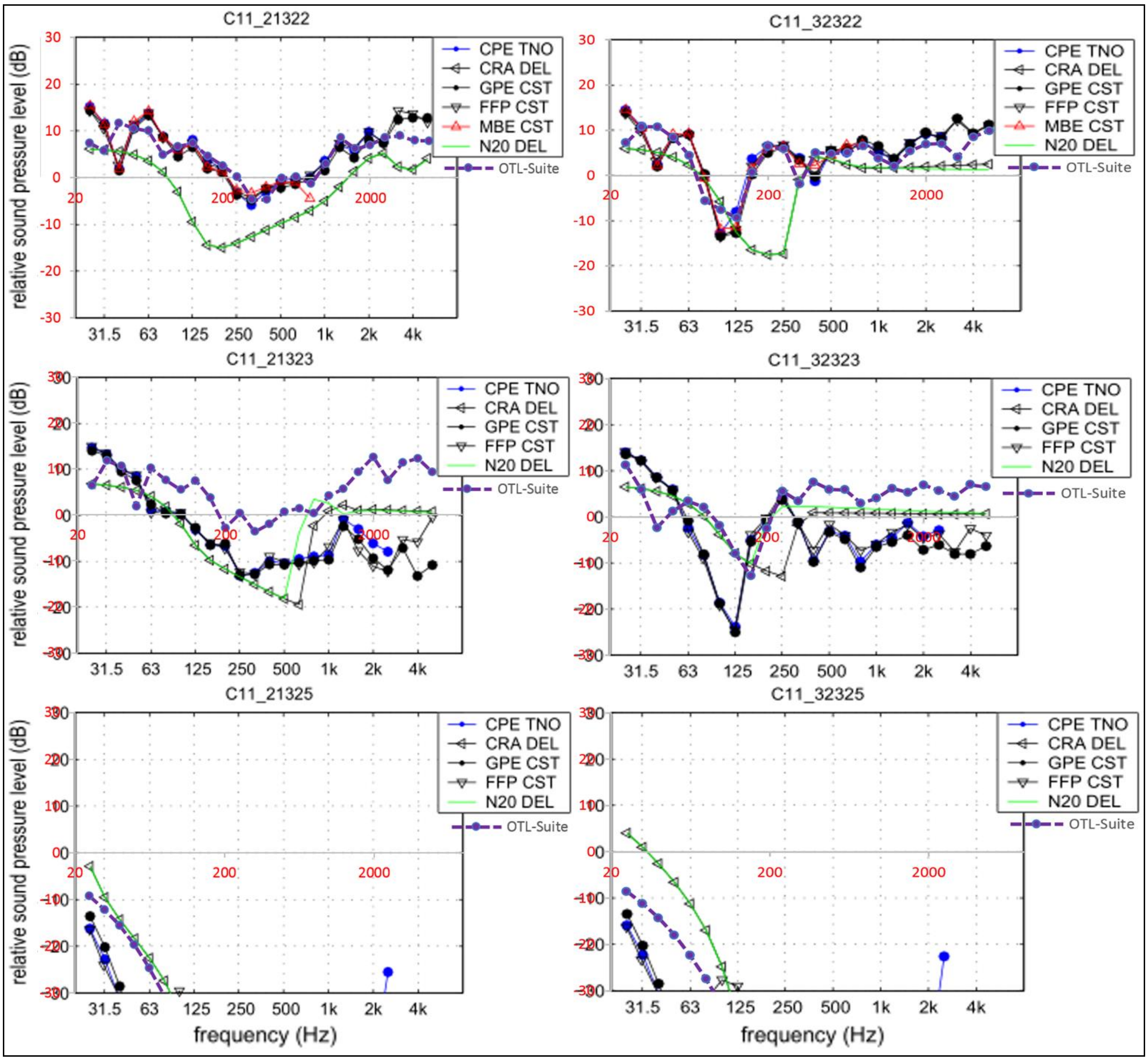

Figure 3: Comparison between OTL-Suite calculations (purple dashed line) and some Harmonoise Benchmark subcases done with various basic and engineering models (see outline in Section 4.2). For the graphs on the left the source and receiver heights are 0.5 and 1.5 m respectively while for the graphs on the right the source and receiver heights are 5 and 4 m respectively. The graphs on the top are for a linear sound speed gradient of the 0.05 s^{-1}, the middle graphs have a positive logarithmic coefficient of 1 ms^{-1} while the bottom graphs have a negative logarithmic coefficient of -1 ms^{-1}. Calculated graphs are superimposed on published data.

The results for the Harmonoise Benchmark subcases are shown in Figure 3 above. For the subcases where the source and receiver are close to the ground (0.5 m and 1.5 m respectively) a good agreement with both basic models and engineering models is found for the case with linear refraction (Subcase C11_21322). Once a logarithmic profile is assumed the results of OTL-Suite and the engineering models deviate from the basic models (Subcase C11_21323) significantly. There is always a frequency shift between the interference minima. This is to be expected because since OTL-Suite and the engineering models use a linear approximation for the logarithmic profile, the path length and time differences will be different leading to a shift of the interference minima.

For the subcases where the source and receivers are further away from the ground (5 m and 4 m respectively) there is a better agreement between OTL-Suite and the basic models for the logarithmic cases (subcases C11_32323) in the low frequencies although there are still high deviations. This is to be expected because of to the shape of the logarithmic curve. As the source and receiver move away from the ground the linear approximation will better match the logarithmic one.

There is also a discrepancy between OTL-Suite and the engineering models in all of the subcases. This can be explained by the fact that the engineering models are single bounce models that only take into account two paths whereas OTL-Suite implements a multiple bounce model. The discrepancy occurs because at long ranges there will be a significant amount of paths for downward refractions which the single bounce models of the engineering models do not take into account.

For subcases C11_21325 and C11_32325 where the receivers are in the shadow zone there is a large deviation between the engineering models and the basic models with OTL-Suite displaying a closer agreement with the basic models.

6. Comparison with noise measurements

For the case of wind turbine noise, the comparisons between OTL-Suite calculations and measurements was done in 2 steps.

In the first step we used the loudspeaker measurements which were made in the framework of the validation of Nord2000 (Plovsing & Kragh, 2009). This step is interesting because the loudspeaker was positioned at a height of 50m, which is comparable to the height of the noise sources of a wind turbine. The parameters used for these cases are detailed in **Table 4**.

In the second step OTL-Suite calculations were compared to noise measurements around a wind farm consisting of 6 wind turbines (hub height 80m). This test case was chosen because in some meteorological configurations (high wind shear in stable atmospheric conditions) the background noise is more than 10 dB lower than the WTN noise, even at ranges of 500m from the wind turbines. High wind shear also has the advantage that it results to a low wind speed near the ground reducing the wind disturbance on the microphone.

Due to the unpredictable range of atmospheric parameters in any given situations we propose a scatter plot of dB(A) values vs the atmospheric parameters for validating atmospheric acoustics.

6.1 Comparison with loudspeaker measurements by DELTA

In this test case the loudspeaker was placed at a height of 50m. The noise source’s amplitude and directivity was known enabling us to calculate the excess propagation effect (the difference between the total sound level and direct sound) in 1/3 octave frequency resolution. Although (Plovsing & Kragh, 2009) used a ground Flow Resistivity of 200000 Pasm^{-2} there is great uncertainty about the ground modelled therefore the value of the Flow Resistivity was adjusted to 400000 Pasm^{-2} for DELTA Case 1 and 50000 Pasm^{-2} for DELTA Cases 2, 3 and 4 in order to match the first interference minimum.

Table 4: Parameters used for the DELTA Validation Cases. Input data taken from (Plovsing & Kragh, 2009) **or extrapolated from their graphical representations of the sound speed profiles. The ground Flow Resistivities were adjusted from DELTA's 200000 Pasm^{-2}.**

Parameter	Delta Case 1	Delta Case 2	Delta Case 3	Delta Case 4
Source Height (m)	50	50	50	50
Receiver Height (m)	2	2	2	2
Ranges (m)	456	1020	412	912
Temperature at Ground (ºC)	4	4	4	4
Temperature Height z (m)	10	10	10	10
Temperature at Height z (ºC)	4.25	4.25	4.25	4.25
Wind Speed Height z_u (m)	10	10	10	10
Wind Speed at Height z_u (ms^{-1})	4.2	4.2	4.2	4.2
Wind Direction relative to Sound Propagation Direction (degrees)	0 (downwind)	0 (downwind)	180 (upwind)	180 (upwind)
Roughness Constant (m)	0.015	0.015	0.015	0.015
Ground Flow Resistivity (Pasm^{-2})	400000	50000	50000	50000

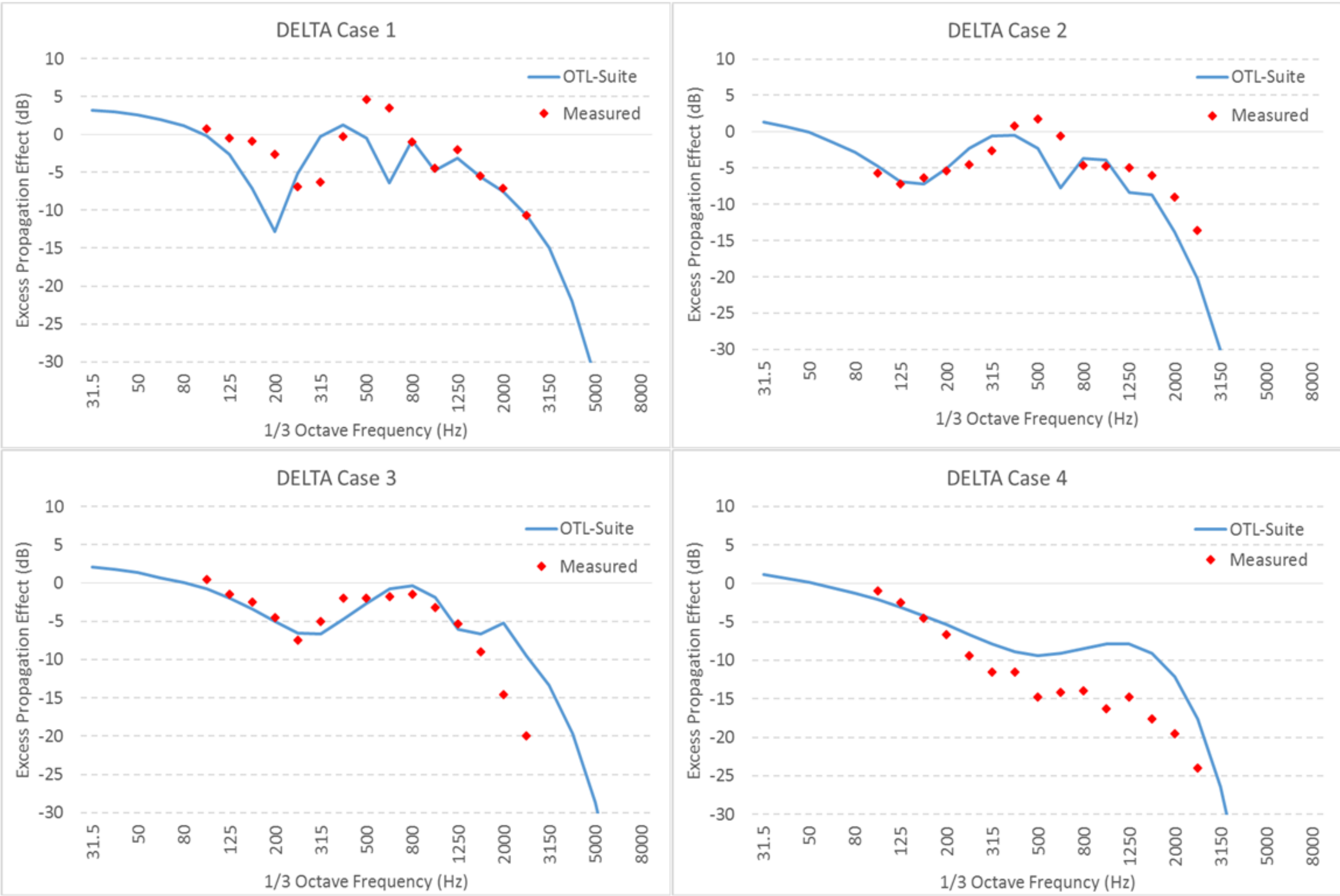

Figure 4: Measured and predicted excess propagation effect. Delta Cases 1 and 2 are for downwind conditions while Delta Cases 3 and 4 upwind conditions. The source receiver horizontal range is approximately 500 m for Cases 1 and 3 and approximately 1000 m for Cases 2 and 4.

Figure 4 above presents the results for two ranges (approximately 500m and 1000m) for both downwind and upwind conditions. There is a good agreement for downwind propagation, and a more or less good agreement in the upwind propagation. This is consistent with the comparisons with the Harmonoise benchmark cases described in Section 5.2.

It is difficult to analyse this case further, because of the reliability of the input data: some of the parameters (like temperature and roughness) had to be extrapolated from the graphical sound speed profiles available in (Plovsing & Kragh, 2009).

6.2 Comparison with noise measurements around a wind farm

The wind farm that was investigated consisted of 6 wind turbines (hub height 80m, rotor diameter 90m). The meteorological measurements recorded were: wind speed and wind direction at heights of 2m, 10m and the hub height of 80m; temperature, humidity and atmospheric pressure at heights of 2m and 10m.

The microphones were positioned at a height of 1.5m and at horizontal ranges of 150m and 500m from the wind turbines; measurements were done in a 1/3 octave band frequency spectrum and full audio spectrum for some locations.

Noise measurements are presented in L_{eq} for a horizontal range of 150m from the wind turbines, and L_{50} for large ranges.

The wind turbine is modelled as a point source. The sound power level of the source is available from measurement reports. There were three cases taken into consideration with the parameters outlined in **Table 5** below:

Table 5: Parameters used for OTL-Suite model to compare against WTN measurements

Parameters	WTN Case 1	WTN Case 2	WTN Case 3
Source Height (m)	80	80	80
Receiver Height (m)	1.5	1.5	1.5
Range (m)	150	500	500
Temperature at Ground (°C)	10.7	4.1	3.6
Temperature Height z (m)	10	10	10
Temperature at Height z (°C)	10.732	4.382	3.757
Wind Speed Height z_u (m)	10	10	10
Wind Speed at Height z_u (ms^{-1})	6.8	5.0	4.4
Wind Direction relative to Sound Propagation Direction (degrees)	Downwind	Downwind	Upwind
Roughness Constant (m)	0.05 (shear factor 0.16)	0.91 (shear factor 0.28)	1.33 (shear factor 0.31)
Ground Flow Resistivity ($Pasm^{-2}$)	225000	225000	225000

The Excess Attenuation is first calculated in narrow frequency bands starting at 20 Hz in steps of 5 Hz until 500 Hz, where the steps switch to 20 Hz until at 10000 Hz. The frequencies of the Excess Attenuation are then combined into the centre frequencies of a 1/3 Octave spectrum ranging from 25 Hz to 10000 Hz. The direct sound (which includes the source characteristics) is then added to the Excess Attenuation in the 1/3 Octave spectrum to obtain the Sound Pressure Level. This is then also combined into a 1/1 Octave spectrum and then given in dB(A) values.

OTL-Suite allows users to calculate the Excess Attenuation at extremely high resolutions (from 0,001 to 100.000 Hz at 0,001 Hz increments, in constant frequency steps or constant percentage steps). The resolution chosen here is a compromise between accuracy and performance.

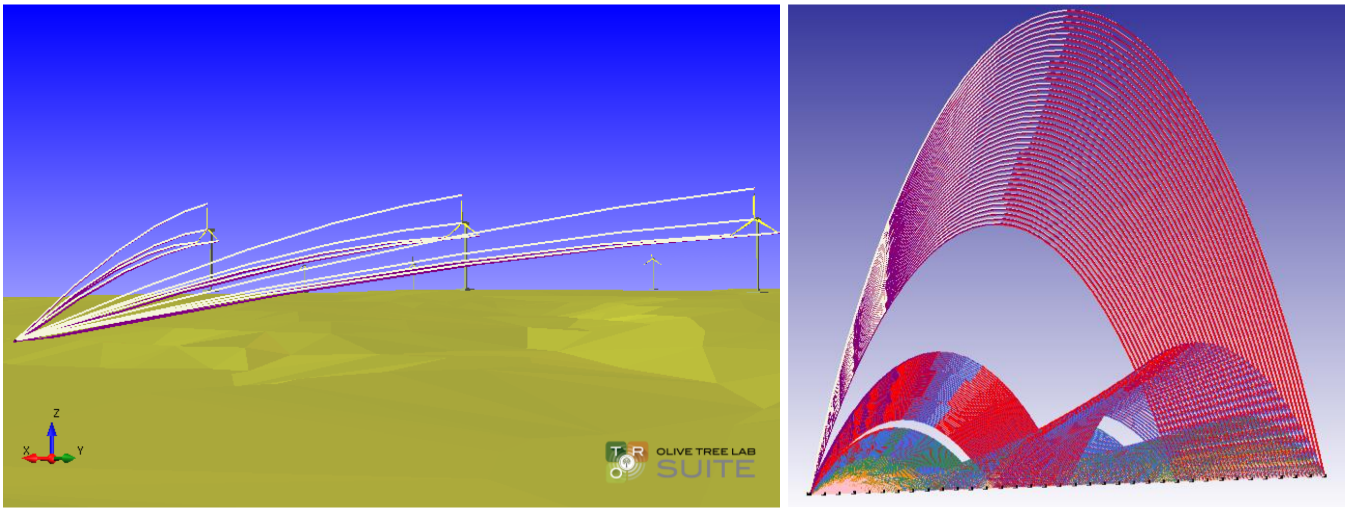

Figure 5: On the Left: View of the 3D model for 3 wind turbines. On the Right: Some of the sound ray paths between source and 80 receivers for the 1995 Benchmark Case 2. The receivers are located at a range of 5000 – 7000 m.

A first comparison is presented in Figure 6 below for WTN Case 1, in a 1/1 Octave band frequency spectrum and 1/3 Octave band frequency spectrum in downwind conditions.
We can see a good agreement between calculations and measurements at a range of 150m of the wind turbine, with almost the same interference minimum at about 125 Hz.
This means that the sound power level taken as input data and the propagation model works fine, even in the point source approximation.

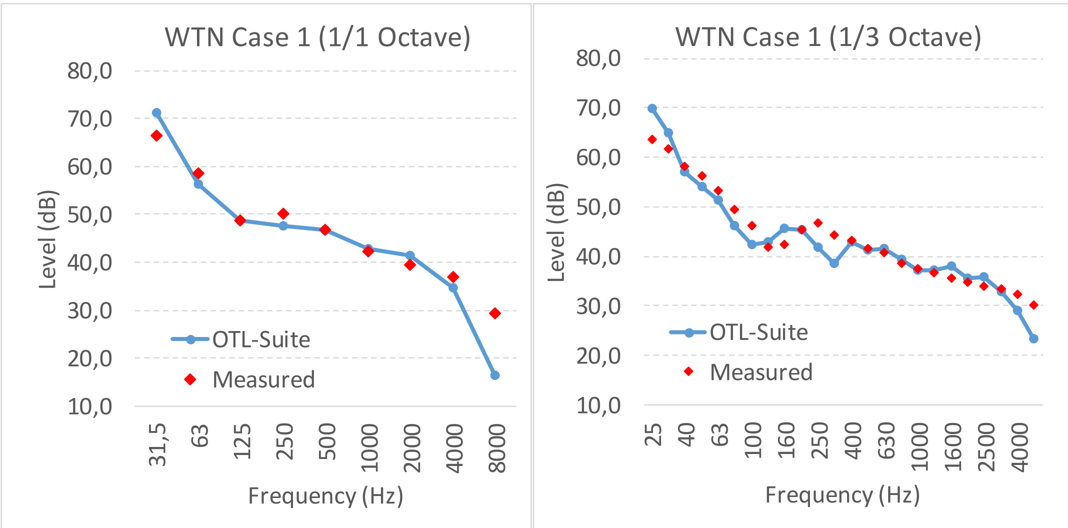

Figure 6: Measured and predicted noise level for WTN Case 1 in 1/1 band and 1/3 band. Downwind conditions with a range of 150m.

Figure 7 below presents the results for WTN Case 2, at a range of 500m from a wind turbine in downwind conditions. Calculations are presented in 1/3 Octave band frequency spectrum, and for a set of 10-minute meteorological data in dB(A).

We can see a good agreement in the 1/3 Octave frequency spectrum with some small differences in the low frequencies under 40 Hz, which were also visible at a range of 150m. There is a very good agreement on the dB(A) scatter plot.

Figure 8 below presents the results for WTN Case 3, at a range of 500m from a wind turbine in upwind propagation.

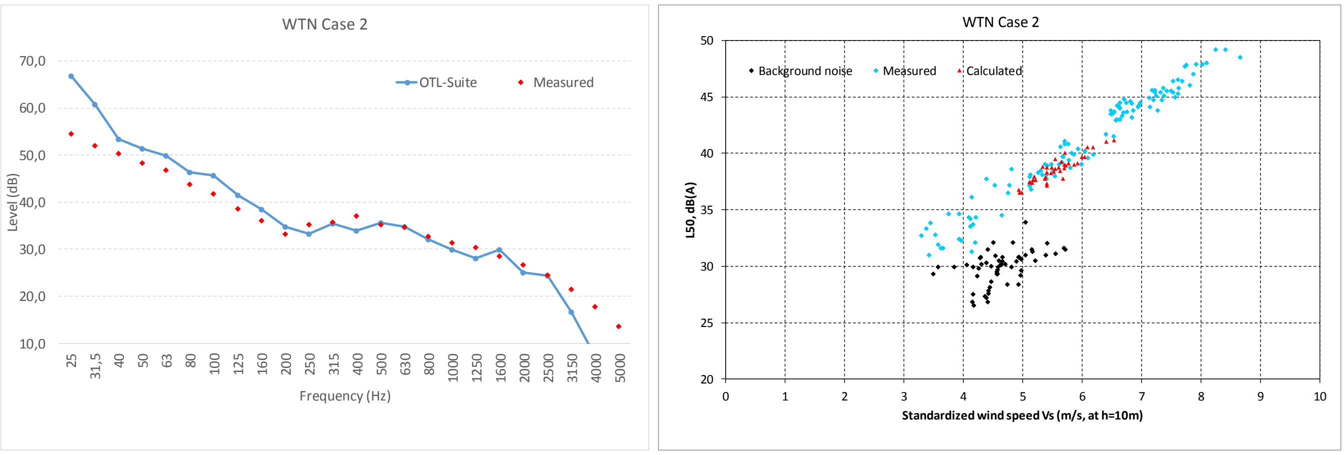

Figure 7: Left graph: Measured and predicted noise levels for WTN Case 2. Right graph: Measured and predicted Noise Levels for Case 2 in dB(A) for a set of 10-minute meteorological data. Downwind conditions with a range of 500m.

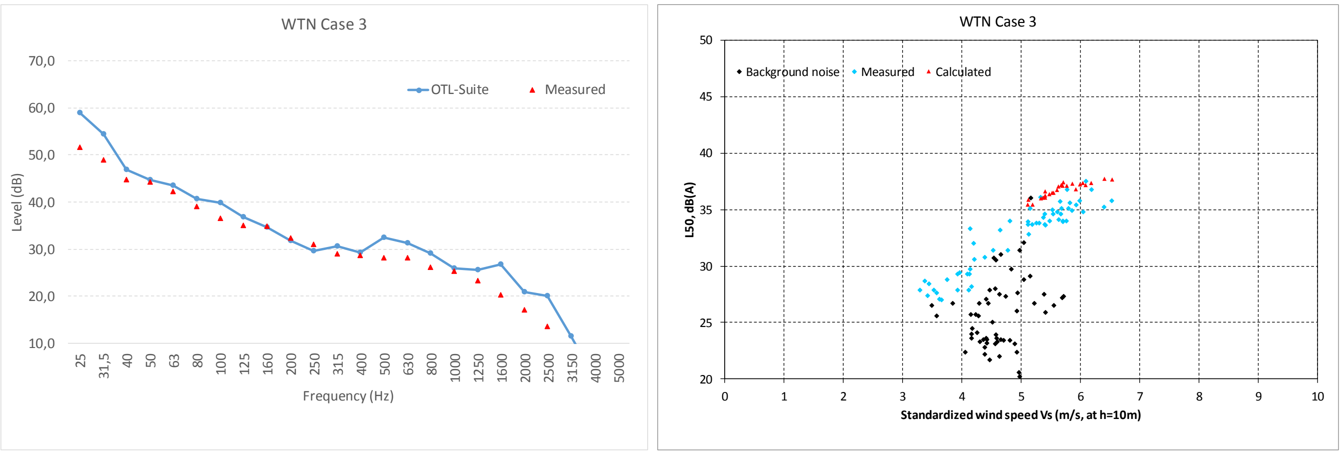

Figure 8: Left graph: Measured and predicted noise levels for Case 3. Right graph: Measured and predicted Noise Levels for Case 3 in dB(A) for a set of 10-minute meteorological data. Upwind conditions with a range of 500m.

We can see some differences between measurement and calculation in the spectrum calculations, but a quite a good agreement in the dB(A) scatter plot. However the calculation results in dB(A) seems to correspond to the maximum of the measured values.

This is consistent with the comparisons between OTL-Suite and the benchmark cases in Sections 5.1 and 5.2. OTL-Suite seems to overestimate the high frequencies at long ranges compared to the basic models. It should also be noted that if the receiver is located in the shadow zone for upwind conditions OTL-Suite will use the default xy plane as the ground and ignore the imported rough ground model. A rough ground would most likely further attenuate the Sound Pressure Levels. Nevertheless the calculated results are within an acceptable range to the measured ones.

7. Conclusion

This paper is a result of a collaborative research between SIXENSE Environment and PEMARD. The calculation results of OTL-Suite are compared with benchmark cases and long term noise & meteorological measurements taken especially for this paper, at a wind turbine farm. Comparison of calculation results with benchmark cases is good. In the case of wind turbine noise there is a very good agreement in the downwind cases and acceptable results in upwind condition. The key point of the calculation is the knowledge of full meteorological data, including wind speed profile and temperature gradient. This can easily be assessed with two meteorological stations at 2m and 10m height, as presented in a previous paper at WTN 2015 (Bigot, Slaviero, Mirabel, & Dutilleux, 2015). A good way of presenting calculation results is to compute one calculation for each 10mn sample of meteorological data, and present the scatter plot of the dB(A) values.

The paper shows that the complexity of atmospheric dynamics cannot be fully represented by a single practical engineering model. This is already demonstrated in the Harmonoise validation reference. The main source of discrepancy between measured and predicted data in ray models is the approximations used in calculating sound speed profiles. However, for engineering purposes accuracy has to be traded with calculation time. This being said, the ray models, implemented with multiple reflection paths, seem to be better suited as a compromise between accuracy and calculation time. Furthermore, sound ray paths allow for the visualisation of sound propagation.

Future work could include the study of subsonic noise propagation in OTL-Suite, which allows calculations of infrasound. In future development of OTL-Suite, noise sources could be modelled as moving dipole and quadrupoles sources (instead of monopoles) allowing for more realistic calculations including the calculation of modulation effects. It would also be worthwhile to compare more measurements with further developments of WBGA to include phenomena such as the semi-analytical model for full logarithmic sound speed profiles (Salomons E. M., 1994), the effects of caustics (Salomons E. M., 1998) and the more recent model of the effect of turbulent scattering of acoustical energy into the shadow zone (Lam, 2009).

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