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MAPPING OF UPWIND AND DOWNWIND AIRBORNE NOISE PROPAGATION

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SUMMARY

Introduction

In France, the noise impact of wind turbines is measured by what is called the "sound emergence". This measured value must not be exceeded. Noise impact studies have to make predictions in order to ensure that this limit is not exceeded and if necessary indicate to wind farm developers how their projects can be modified to satisfy this requirement. These modifications often consist in decreasing the number of wind turbines in operation if the weather conditions would cause the legal limits to be exceeded. Therefore these conditions have to be identified as closely as possible.

Weather conditions have an impact on sound propagation and are one of the parameters which influence this "sound emergence". The noise level may vary considerably upwind and downwind of a noise source. The models used for the impact assessment should take into account the weather conditions which are least propagators of noise emissions so that the operation of the wind turbines can be adjusted to suit these conditions. Thus, models which are defined for airborne noise emissions only (such as ISO 96-13) are not sufficient to cover these particular site characteristics. Moreover, in France, wind turbines are often installed on hilly terrain. The models must therefore take into account the influence of topography on sound propagation.

This paper describes a model which has been developed and used for making operational forecasts (short calculation, time, noise map plotting, etc.) suitable for use with wind-farms.

It differs from the conventional models of specular reflection in that it is based on the assumption that the sound waves are diffused on their reflection by the ground. We will describe this aspect of the model in the first part.

The meteorological characteristics are defined by temperature and wind speed changes at height. The orientation of the wind is also taken into account and is assumed to be constant at the height covered by the calculation. We will described the method used to cover these parameters in the second part.

These characteristics enable the speed of sound propagation with height to be evaluated and the sound wave refraction to be deduced. This enables the sound wave curve to be evaluated. When the curved sound waves come into contact with the ground (taken into account together with its topography by the model) or any other type of obstacle, the model evaluates the diffraction and the sound energy which result. We will describe the calculation method in the third part.

Ultimately, the model allows the noise map to be plotted for complex topographies in both good and poor airborne noise propagating conditions (upwind and downwind). Measurements and calculations have been carried out in real situations and we describe them in the conclusion to this paper.

The ground considered as diffusing planes

The models for predicting the sound field based on specular reflection assumptions use infinitely smooth surfaces. However, in the case of rough surfaces and dimensions less than the wavelength, experiments have shown that specular reflection of the sound no longer applies. In France, wind turbines are generally located in rural zones where the ground is seldom smooth and flat. To take account of these ground conditions, a diffuse reflection model has to be used.

Our model assumes [23], [25], [26] that the intensity of the noise at any point above the ground consists of two superposed components, a direct component consisting of the intensity of the noise emitted directly by the source, and a component of noise reverberated from the ground, buildings or other obstacles. The first component, which is easily determined, corresponds to the free field propagation of spherical waves, the theoretical model for which is well known. The second component (reverberated noise) requires the assimilation of the floor and any walls of buildings as point sources (virtual) the directivity of which takes account of the diffusion assumption.

The directivity factor of the diffused reflection used by our model is:

$$Q(\theta) = 4\cos\theta$$

Each component of a surface which receives energy retransmits it towards all the surface components. Let us examine two components dS and dS' centred respectively on x and x',

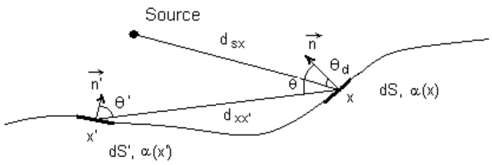

Figure 1: influence of a ground element on another one

These elements are both characterized by their absorption coefficients $\alpha(x)$ and $\alpha(x')$. The surface density of incident power on dS, noted dI(x) and induced by dS', is:

$$dI(x) = \frac{I(x')(1-\alpha(x'))\cos\theta'\cos\theta\, dS'}{\pi d_{xx'}^2}$$

cos θ is the solid angle according to which dS is seen by the incoming flux.

$I(x')$ is the surface density of incident power on dS', only the fraction $I(x')(1-\alpha(x'))$ of which is re-emitted.

In order to simplify the formula, we have grouped the geometrical terms within the same coefficient, that we can call the influence coefficient K(x,x').

$$K(x,x') = \frac{\cos\theta\cos\theta'}{\pi d_{xx'}^{\ 2}}$$

thus,

$$dI(x) = I(x')(1-\alpha(x'))K(x,x')dS'$$

The surface density of incident power on dS induced by the surfaces considered (ground, buildings, etc.) is therefore

$$I(x)=\int_{S'} K(x,x')I(x')(1-\alpha(x'))dS'$$

This expression would not be complete if we did not take into account the intensity of the source received directly by dS. This intensity is represented by $I_{d,x}$. The surface component dS has an angle θ_d between its normal and the source. The direct intensity is expressed by:

$$I_{d,x}=\frac{W.Q_S(\theta_d)\cos\theta_d}{4\pi d_{sx}^2}$$

where d_{sx} represents the distance separating the source from the element centred on x, and $Q_S(\theta_d)$ the directivity coefficient of the source.

Therefore we obtain:

$$I(x)=\int_{S'} K(x,x')I(x')(1-\alpha(x'))dS'+I_{d,x}$$

In order to overcome the integral and allow the equation to be solved numerically, the walls have to be discretised. Therefore the walls have to be broken down into N surface samples by considering that:

- the absorption coefficient α is constant for a same sample
- the surface power density is constant on all the surface S_i of the sample
- each surface sample will be identified by its centroid.

Thus, for a receiving sample S_i, the surface power density is expressed by:

$$I_i=\frac{1}{S_i}\int_{S_i}\int_{S'} I(x')K(x,x')(1-\alpha(x'))dS_i dS'+I_{di}$$

where $I_{di}=\frac{WQ_S(\theta di)\cos(\theta_{Si})}{4\pi d_{Si}^2}$ is the power density coming directly from the source and received by sample i at moment t,

where θ_{Si} is the angle between the normal on the surface of sample i and the source,

and d_{Si} the distance separating the source from sample i.

Similarly, all the emitting surfaces are discretised as surface samples S_j of absorption coefficient α_j and surface power density I_j.

The equation then becomes:

$$\boxed{I_i=\sum_{j=1}^{N} I_j(1-\alpha_j)K_{ij}+I_{di}}$$

where ed_{ij} is the distance between the centroids of samples i and j, and with $K_{ij}=\frac{1}{S_i}\int_{S_i}\int_{S_j} K(x,x')dS_i dS_j$, which we can approximate as:

$$K_{ij}=\frac{\cos\theta_{ij}\cos\theta_{ji}S_j}{\pi d_{ij}^2}$$

The above equation can be written as:

$$I_i-\sum_{j=1}^{N}I_j\left(1-\alpha_j\right)K_{ij}=Id_i$$

Let us define a square matrix A of dimension (NxN), N being the number of surface samples with coefficient a_{ij} such that:

$$\begin{cases}a_{ii}=1\\a_{ij}=K_{ij}\left(1-\alpha_j\right)\end{cases}$$

i = line index

j = column index

This equation can be written in matrix form: $I.A=Id$

where I is the column vector for the power surface densities of dimension (Nx1) and I_d the column vector for the intensities received directly from the dimension source (Nx1).

Vector I is determined by simple solving of this matrix equation by inverting the matrix A.

$$I=A^{-1}.Id$$

Knowing the values of vector I, we are able to determine the acoustic intensity received at any point. We will spare the reader the other stages similar to those which we have just described and pass directly to the results which are:

$$I_R=\frac{W}{4\pi d_{SR}^2}+\sum_{i=1}^{N}\frac{I_i\left(1-\alpha_i\right)\cos\theta_{ri}S_i}{\pi d_{ri}^2}$$

The pressure level is obtained by:

$$L_p=10\log\left(\frac{I_R}{10^{-12}}\right)$$

Weather characteristics

In the context of a wind turbine impact study, we seek to calculate the noise levels far from the sources. Any changes in the characteristics of the atmosphere will have an influence on the result. Two phenomena are to be taken into account:

- The change of sound velocity with altitude leading to the refraction of the sound waves
- The absorption of sound by the atmosphere

This latter point is included in our model, as proposed by standard ISO 96-13 Part1. Thus we will not expand on it further here and will examine the refraction phenomenon.

The celerity of sound is written $c=\sqrt{\frac{\gamma RT}{M}}$ where:

- γ is the relationship between the specific heat at constant pressure (C_p) and the specific heat at constant volume (C_v), i.e. $\gamma = \frac{C_p}{C_v}$,
- R is the constant of perfect gases equal to 8314.16 $JK^{-1}mol^{-1}$,
- T is the temperature in °K,
- M is the molar mass in $g.mol^{-1}$.

We notice that the celerity of sound depends on the temperature. The wind can also be taken into account in the formula for the speed of sound by using an effective celerity $\vec{c}_{eff} = \vec{c} + \vec{v}$ where $\vec{c}$ and $\vec{v}$ are respectively the celerity of sound and the wind speed.

The parameters γ and M are related to the moisture content of the air. It can be seen that changes to moisture content with altitude lead to variations of celerity that are negligible compare to those induced by the temperature variation. [8].

Thus we will concentrate on assessing the variations in temperature and the wind speed with altitude.

The equation for movement is written as follows (non turbulent atmosphere):

$$\frac{d\vec{V}}{dt} = \vec{g} - \frac{1}{\rho}\vec{\nabla}P - 2\vec{\Omega} \wedge \vec{V} + \vec{F_v}$$

where:

- $\vec{g}$ is the force of gravity,

- $\frac{1}{\rho}\vec{\nabla}P$ is the pressure force,

- $2\vec{\Omega} \wedge \vec{V}$ is the Coriolis effect due to the rotation of the earth,

- $\vec{F_v}$ is the friction force.

Close to the ground (in the layer next to the surface), it may be considered that the pressure force and the Coriolis effect are negligible relative to the friction forces. Therefore, we can show ([3],[15]) that the speed of wind at altitude z is:

$$\bar{u}(z) = \frac{u*}{k}\ln\left(\frac{z}{z_0}\right)$$ where:

- u* is the friction speed which depends on the surface and the meteorological conditions (sunshine, etc.),
- k is Karman's constant, equal to 0.4 in the atmosphere,
- z_0 is the roughness length, corresponding to approximately 10% of the height of obstacles.

It is also shown [15] that the temperature in the layer next to the surface at altitude z can be evaluated as follows:

$T(z)=T_h+\frac{T_* Pt}{k}Ln(\frac{z}{h})$ where:

- T_h is a reference temperature at altitude h,
- $T_* = \frac{-Q_s}{U_*}$ (7) where U_* is the friction speed in $m.s^{-1}$,
- $Q_s = \frac{-H_s}{\rho C_p}$ where H_s is the sensible heat flux in $W.m^{-2}$,

Comments: Pt is a constant of 0.74. Sensible heat is the heat emitted or absorbed by the earth leading to a temperature increase or decrease (for example nighttime temperature inversion).

The refraction influence

The variation in the temperature and the wind speed with altitude induces a celerity change with altitude which leads to refraction of the sound waves propagated in the atmosphere. This well-known phenomenon leads to curvature of the sound waves. There are complex models for solving the parabolic approximation of the Helmoltz equation which translates acoustic wave propagation (FFP [27], PE [27], GF-PE [27], Split-step Padé [20, 4], LE and Lagrangien Model [31]) exist. They are expensive in calculation time and cannot be easily adapted to operational applications such as ours. This is part of the geometrical acoustic approximation. In our case, it consists in determining[1] the trajectory of the "ray" of sound. This results from the integration of the following equation:

$$\frac{dz}{dx} = \frac{c(z)\,\cos i(z)}{c(z)\,\sin i(z) + U(z)}$$

where $c(z)$ is defined by $c(z) = \sqrt{\frac{\gamma R T(z)}{M}} + u(z) * \cos\beta$ and the terms used are as follows:

- $u(z) = \frac{u*}{k}\ln(\frac{z}{z_0})$, is the wind;
- $T_1(z) = T_h + \frac{T_* Pt}{k} Ln(\frac{z}{h})$, is the temperature;

The trajectory is curved and the curvature is oriented towards the ground or towards the sky. In the latter case, from a certain distance there would no longer be any acoustic energy coming from the source (shadow zone, see opposite). However, experience has shown the existence of energy in this zone. Several factors explain this

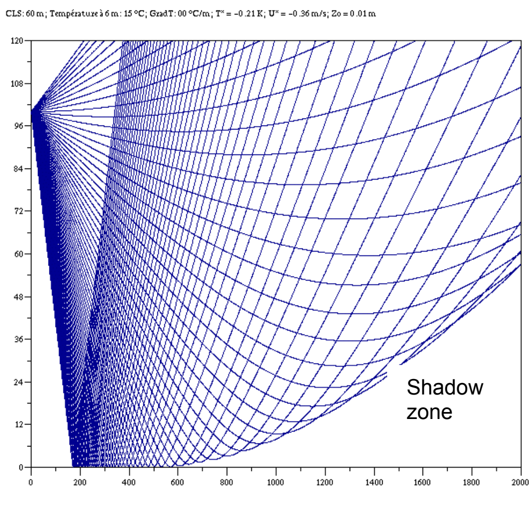

Figure 3 – a few plotted trajectories on flat ground

[1] And use of this trajectory in the model presented in part one

acoustic irrigation of the shadow zone (presence of turbulence in the atmosphere which diffuses the sound energy, diffraction of sound waves by the ground, etc.)

At present, our model takes into account this shadow zone irrigation phenomenon by the diffraction of the sound wave on the ground and by diffusion of the sound energy striking the ground.

Comparison of the calculated results with measured results

In this paper, we present the results obtained on three different wind farm sites. An impact study type of approach has been used to measure the noise level. The purpose of this approach is not to detail its thoroughness[2] (note that a summary is provided in the Appendix). These results are meant to be representative of the noise level generated by the wind turbines alone (i.e. corrected for background noise).

Site 1

This is a rural site with bush and tree vegetation.

There are six wind turbines on this site (80 m hub height). The ground is to be modelled in the form of a plane (maximum level difference of about 30 m at a distance of 500m). The image below schematises the position of the wind turbines (red points) and the reception points at which the measurements were made:

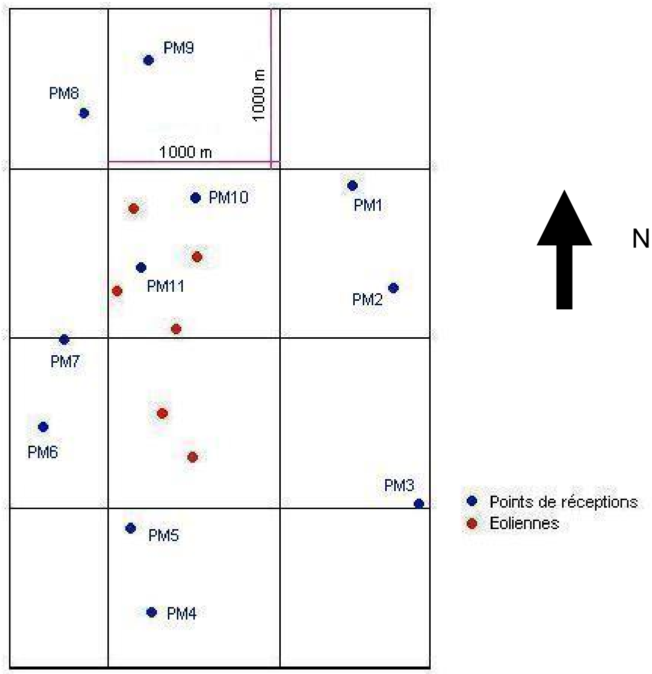

Figure 4 – Site 1

The results of the measurements (which will be compared with the computed results) correspond to a period of nighttime operation with a south-westerly wind and

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[2] The difficulty of measuring the impact of a wind farm is associated with the fact that the noise generated by the wind turbines is often drowned in the background (caused by the wind). The measurement procedures used in France are becoming standardized. A draft standard is currently being prepared. The procedures used for taking the measurements as described in this paper are in line with this draft standard.

a mean wind speed of 2.7s at 10 m above the ground. The average temperature during this period is 9°C.

The results are presented in the table below.

	Dste S-In m	Direct° Prop	Laeq,cor'ted
PM1	**1000**	**downwind**	25
PM2	**1070**	**Slightly downwind.**	32 to 39
PM3	**1220**	**crosswind**	26
PM4	**840**	**upwind**	38 to 46
PM5	**560**	**upwind**	27
PM6	**710**	**Slightly upwind.**	28.5
PM7	**400**	**crosswind**	29
PM8	**530**	**Slightly downwind**	25
PM9	**800**	**Slightly downwind**	28 to 38
PM1	**300**	**downwind**	33.5
PM1	**300**	**downwind**	38

Table 1 – Results of measurements on site 1

The shaded boxes in this table correspond to configurations at which the noise level generated by the wind turbines alone is drowned by the background noise observed. For information, these boxes indicate Leq1mn values between which the background noise fluctuated.

The parameters used in the calculation to characterize the wind and temperature, and corresponding to the measurements made, are: u*= 0.69, z_0=0.2, T*= 0.32, Th=9°C, h=10m. The acoustic powers of the sources were measured on the site (in accordance with the stipulations of standard IEC 61400-11).

The following table gives the computed results obtained compared with the measured results.

	Dste S-R in m	Direct° / Propa	Leq db(A) **Meas.**	Leq dB(A) **Calcul**
PM1	**1000**	**downwind**	25	25.1
PM2	**1070**	**Slightly downwind.**	32 to 39	24.3
PM3	**1220**	**crosswind**	26	22.5
PM4	**840**	**upwind**	39 to 46	21.7
PM5	**560**	**upwind**	27	26.9
PM6	**710**	**Slightly upwind.**	28.5	26.3
PM7	**400**	**crosswind**	29	30.4
PM8	**530**	**Slightly downwind**	25	29.4
PM9	**800**	**Slightly downwind**	28 to 38	26.7
PM10	**300**	**downwind**	33.5	35.3
PM11	**300**	**downwind**	38	38.5

Table 2 – Computed results for site 1

A comparison of the measured results and the computed results shows good concurrence.

<u>Site 2</u>

This is a rural site with bush vegetation.

There are eight wind turbines on this site (40 m hub height). The turbines are situated on a crest and the relief is broken. The specific characteristic of this analysis is that the measurements which we made always showed that at distance greater than 900 m from the wind turbine line the noise generated by the wind turbines is drowned in the background noise. However, one point concerning the validation of this calculation model appears interesting to us. The image below schematises the wind turbines (red points) and this point of reception:

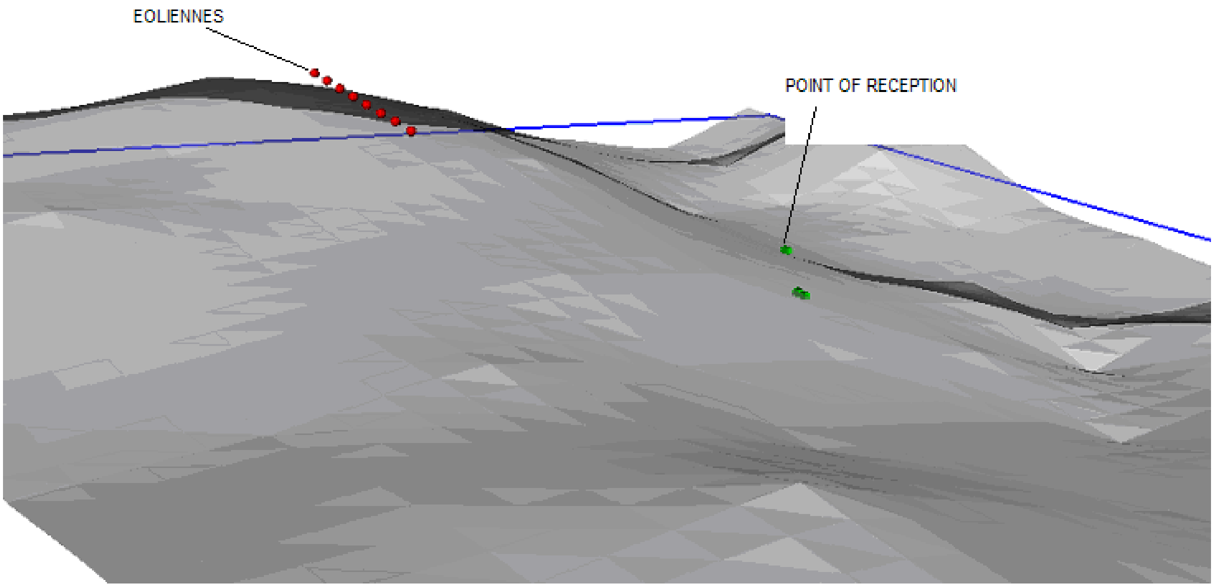


Figure 5 – Site 2

This point is interesting in that it is critical with regard to the combined influence of the topography and refraction. It is located at a lower level (approximately 250 m lower), and a distance ranging between 1000 and 1500 m from the wind turbines. The wind turbine line is not directly visible from this point. However, the noise generated by the wind turbines is slightly audible, whereas the noise level in dB(A) is not impacted by the operation of the wind turbines. This means that the noise of the wind turbines alone is less by several dB(A) than the measured noise level, but the audibility means that the difference between the wind turbine noise alone and the measured noise is less than 10 dB(A). A calculation which does not take into account the influence of refraction but takes account of masking by the topography gives a noise level 20 dB(A) less than the measured noise level at this point. Therefore refraction obviously has an impact at this point.

The measurement results with which we compare the computed results cover a nighttime period with a west-north-west wind at a mean wind speed of 6 m/s 10 m above the ground. The average temperature during this period is 18°C.

The noise level in these conditions is slightly above 30 dB(A), whether the wind turbines are operating or not.

The parameters used in the calculation to characterize the wind and temperature and the corresponding measurements made are: u*= 0.52, z_0 = 0.1, T*= 0.32, Th= 18°C, h=10m. The acoustic powers of the sources are those communicated by the manufacturer.

The noise level obtained by calculation is 28 dB(A), which is what was expected.

Site 3

This is a rural site with bush and tree vegetation.

There are 21 wind turbines on this site (40 m hub height). As with site 2, they are on a crest and the relief is broken. The level difference between the highest wind turbine and the lowest point of reception is approximately 200m.

The image below represents the position of the wind turbines (red points) and the points of reception at which the measurements were made.

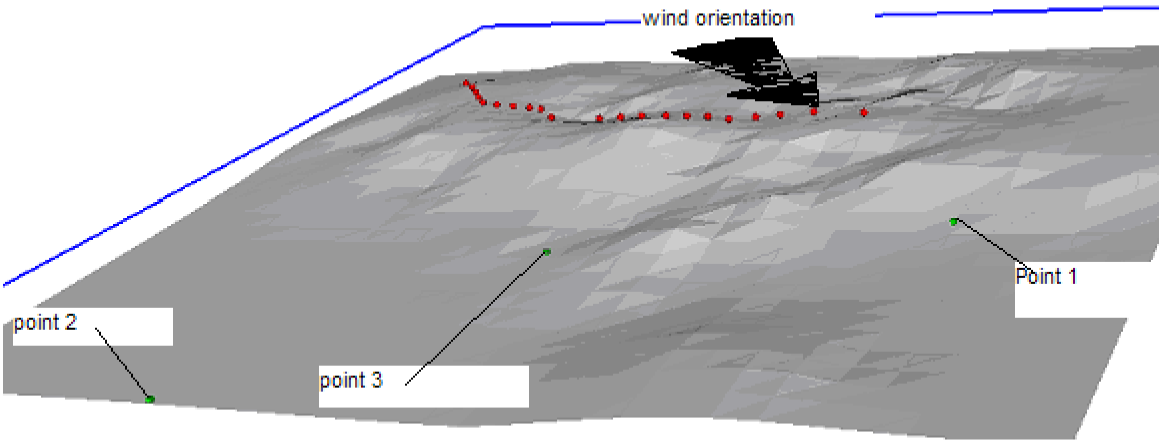


Figure 6 – Site 3

The distance between point 1 and the wind turbines is between 600 and 2100 m, 1600 and 2100 m between point 2 and the wind turbines, and 700 and 1500 m between point 3 and the wind turbines. There is a pine forest close to point 1 which masks the wind turbines from this point.

The measurements compared with the computation results correspond to nighttime operation with a north-east wind at an average wind speed of 6m/s 10 m above the ground. The mean temperature during this period is 10°C.

The table below gives these results.

Points	Leq dB(A)
1	29
2	33.5
3	39

Table 3 – Results of measurements on site 3

The parameters used in the calculation to characterize the wind and temperature, and corresponding to the measurements made are: u*= 0.61, z_0 =0.2, T*= 0.32, Th=10°C, h=10m. The acoustic powers of the sources are those communicated by the manufacturer.

The following table shows the computed results obtained compared with the measured results.

Points	measured dB(A)	Calculated dB(A)
1	29	36
2	33.5	35
3	39	41

Table 4 – Computation results for site 3

At present, our model does not take into account the influence of an attenuation due to crossing a forest. This is most probably the cause of the difference between the calculations and measurements at point 1. It is an improvement to be made. At the two other points, the comparison of the measured results with the calculated results show relatively good concordance.

CONCLUSION

The model that we have presented in this paper can be used to assess the noise impact of wind turbine farms by accurate calculations which match the accuracy of measurements and take account of the main factors that influence sound propagation over long distances. These factors are atmospheric absorption, refraction, diffusion and diffraction on the ground, and topography.

This model is sufficiently operational to allow dimensioning of scenarios in the context of wind turbine impact studies, and to plot useful sound maps for communication to residents living close to wind turbine farms.

Appendix: measuring of a wind farm acoustic impact over long distances

This consists in simultaneously measuring:

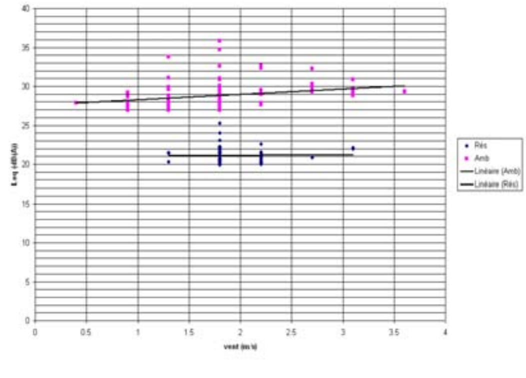
- the noise level in dB(A) at a certain number of points
- the wind speed and the temperature at a height corresponding to a point of reception

Measurements are carried out during operation of the wind turbines, but also during one or more of its shutdown periods.

The equipment consists of an accurate storage integrator sound level meter (class 1 within the meaning of standard NF S 31-009 and NFS 31-109).

The measured Leq levels are integrated for a period of 1 second. From these results we have removed the results which it is felt represent a particular sound event (such as the passage of a vehicle). The Leq 1s are integrated per periods of 1 minute (Leq1mn).

This indicates the evolution of these Leq1mn in relation to the wind at each reception point (see curves opposite). Two groups of results are identified: those with the wind turbine operating (amb: ambient) and those with the wind turbines shut down (res: residual). A trend curve is evaluated for each group of points (by regression). From these curves we deduce a value for the sound level that is considered representative



of a wind speed. The sound level which represents the impact of the wind farm is obtained by correcting the ambient level (amb) using the residual level (res).

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