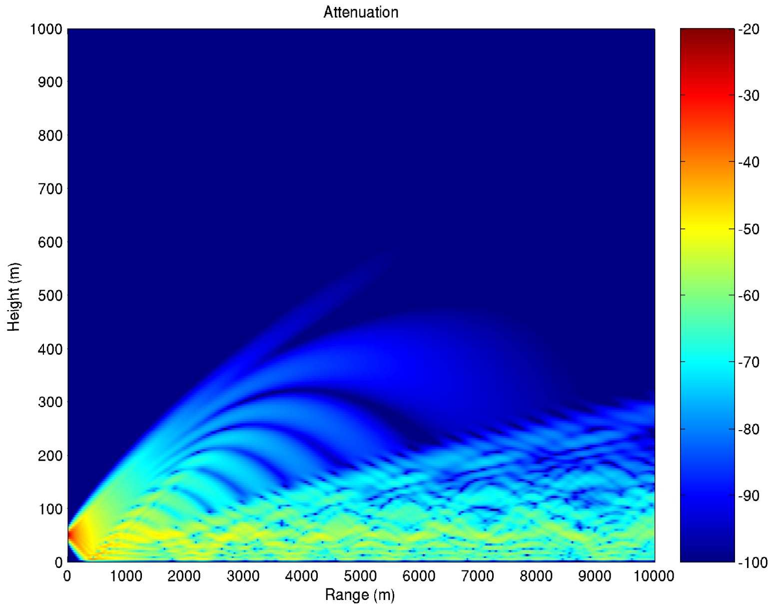

Noise propagation in the atmosphere from wind power plants

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Report's title

Noise propagation in the atmosphere from wind power plants

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Summary

To accurately predict the spreading of sound from a noise source to environment is a demanding task. The complexity of the subject increases exponentially while distances grow. There are many different applications calling for better prediction methods and sound propagation models. Wind power plants are giving their contribution to the work. The literature review shows that a good enough understanding of some physical phenomena connected to outdoor sound propagation is still not obtained, turbulence being one of the most challenging. Evaluation of sound propagation algorithms needs extensive and carefully validated long-term measurements.

Confidentiality Public

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Contents

Chapter 1

Introduction

Research activity in the field of outdoor sound propagation has been increasing noticeably during the last ten years. The importance of weather conditions on sound propagation has been recognized and serious research campaigns have been carried out. In European Union, the Directive 2002/49 [1], relating to the assessment and management of environmental noise, launched work [2] on harmonizing the computational noise mapping methods [3], presenting the state-of-the-art [4], and guidelines [5].

Many different computational tools for calculation of sound propagation have become available. There are analytical solvers, standardized ray tracing based techniques [6] which include interaction with a complex impedance boundary, Gaussian beam ray trace algorithms [7], and many methods to approximately solve the full wave equation, like the parabolic equation (PE) [8–10], the fast field program (FFP) [11], and their hybrid combinations [12, 13].

Even the most recent and complete models of sound propagation lack for information of *accuracy* and *uncertainties*. If the comparison of the accuracy is made between different models [14], the models can be categorized e.g. to simple, like ray tracing based or more complex, like solvers of the wave equation. Typically, the results from simple models differ from complex models with certain input parameters, but being very close to each other within same category. However, the uncertainties of the models cannot be determined without comparison to the reality. With some evaluations it is possible to use scale models [15]. As long as there has been computational models, there has been long-term measurements, unfortunately too often unproperly organized. Common flaws are measurements without any information about environmental changes or changes in the source of sound, and the most typical problem is deficient meteorological data. Depending on the distance between source and receiver(s), there should be enough instrumentation capable of characterizing both the vertical and horizontal gradients of wind and temperature in the atmospheric boundary layer (ABL). To be able to do this, meteorological towers, wind profilers and real soundings must be exploited. Directive 2002/49 [1] says that sound levels should be determined ”*over all the day periods of an year, and the year is a relevant year as regards the emission of sound and an average year as regards the meteorological circumstances*”.

Chapter 2

Theoretical background

Many physical quantities and phenomena have effect on outdoor sound propagation. The properties of the sound source and location of the source are distinct, but usually also definable, measurable and most important — predictable. Generally, the distances between the sound source and immission areas are orders of magnitude greater than the dimensions of the source and distinct sources can be considered as point sources. The sound propagation path (or paths) can be much more complex to define and this theory and the problematics faced with the practice is discussed in the following.

The theory of atmospheric sound propagation is well presented in the literature and good reviews of the basics can be found [16–19]. According to the literature mentioned, the most important physical phenomena on outdoor sound propagation are *absorption*, *refraction*, and *scattering*. Scattering is a common name for different phenomena changing the propagation direction of a sound wave. Scattering consists for example of diffraction or reflection according to Snell's law. However, because refraction is not a consequence of the effect of obstacles to the propagation path, it does not belong to scattering.

2.1 Calculation of noise

Commercial mapping software available today rely on a couple of simplifications and assumptions about the behaviour of a sound wave. First, the sound is considered as rays, behaving like light. It is simple to draw rays from the source and map the places where they hit. The attenuation of a ray is calculated using the inverse square law, i.e. doubling the distance from the source drops sound pressure level by 6 dB. It is possible to include some simple phenomena like air absorption and refraction to the propagating sound ray. Propagating sound wave loses energy by absorption, which is determined by air temperature and humidity (Fig. 2.2). For example the diffraction is more complex and turbulence is practically impossible to implement to ray algorithms. Also, it would be possible to handle non-homogeneous atmosphere and irregular terrain, but none of the commercial ray-theory based software take these into account.

The noise emitted from a wind mill has some characteristics which makes the use of commercial mapping software useless. The source is located high from the ground, where wind has a dominating role to the propagation path. The vertical wind profile changes sig-

nificantly due to the height and has a substantial effect on sound propagation path. The commercial mapping software don't deal with wind profiles. Furthermore they don't take into account the lapse rates, or changing ground impedances.
Most calculation software presume the sources are omni-directional. The directivity of the source may affect the results also due to simplifications made in the software [20].
The exact value for the sound pressure in every position of the atmosphere or ground surface can be solved using the Helmholtz wave equation (2.1)

$$\nabla^2 p_c + k^2 p_c = 0, \tag{2.1}$$

which can be written in three dimensional cylindrical coordinate system (2.2)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p_c}{\partial r}\right) + k_{\mathrm{eff}}^2 \frac{\partial}{\partial z}\left(k_{\mathrm{eff}}^{-2}\frac{\partial p_c}{\partial z}\right) + \frac{1}{r^2}\frac{\partial^2 p_c}{\partial \phi^2} + k_{\mathrm{eff}}^2 p_c = 0, \tag{2.2}$$

where p_c is the complex amplitude of the sound pressure, (r,ϕ,z) are the distance, azimuthal angle, and height in the cylindrical coordinates, k is the sound wave number, and k_{eff} is the effective wave number. The effect of all the known physical phenomena can be taken into account with this simple looking wave equation (2.1), including atmospheric turbulence and irregular, layered terrain. For example, a porous ground surface can be included using a boundary condition (2.3) [21]

$$\left(\frac{p_c}{v_{c,n}}\right)_{n=-\varepsilon} = Z\rho c, \tag{2.3}$$

where $\varepsilon > 0$, $\varepsilon \to 0$, Z is the normalized impedance of a locally reacting ground surface, ρc is the impedance of air just above the ground, and $v_{c,n}$ is component of the complex amplitude of acoustic fluid velocity normal to ground surface.
Turbulence is the most complicated phenomenon to be taken into account. Turbulence is caused by shear forces between the ground surface and wind flow (kinetic turbulence) and by buoyancy forces (thermic turbulence). Many theories about scattering caused by turbulence can be found from the literature. A good review of these theories is by Wilson et al. [22]. Most typical approach to estimate the sound scattering by turbulence is based on the vortex size, or more specifically, the turbulence wave number.
The turbulence wave number $\mathbf{k}_t$, which apply to the scattering detected in direction θ (in respect of x-axis, $\mathbf{e}_\theta =$ is a unit vector in direction of θ) can be defined

$$\begin{gathered} \mathbf{k}_t = k\left(\frac{r}{|r|} - \mathbf{e}_x\right) = k_t \mathbf{e}_\theta \\ k_t = 2k\sin\left(\frac{\theta}{2}\right) . \end{gathered} \tag{2.4}$$

Different definitions for the turbulence wave number spectrum exists: for example Kolmogorov [23, 24], Gaussian [25, 26], and von Kármán [27]. The scattering due to turbulence is dominated by eddies with sizes of the order of the wavelength of the sound waves. This can happen in the *drive* or *inertial* subranges (Fig. 2.1), depending on the geometry and the atmospheric conditions. The dissipation subrange is negligible due very small eddies compared with acoustical wavelengths.

The theoretical turbulence models don't apply very well to the real atmospheric turbulence due to many reasons. The Gaussian and von Kármán spectra are valid only if the turbulence is homogeneous and isotropic. In the real atmosphere, the scale of the turbulence varies as a function of height from the ground. One reason why the real atmospheric turbulence is always anisotropic is because the correlation length parallel to the wind vector is larger than the correlation length perpendicular to the wind vector.

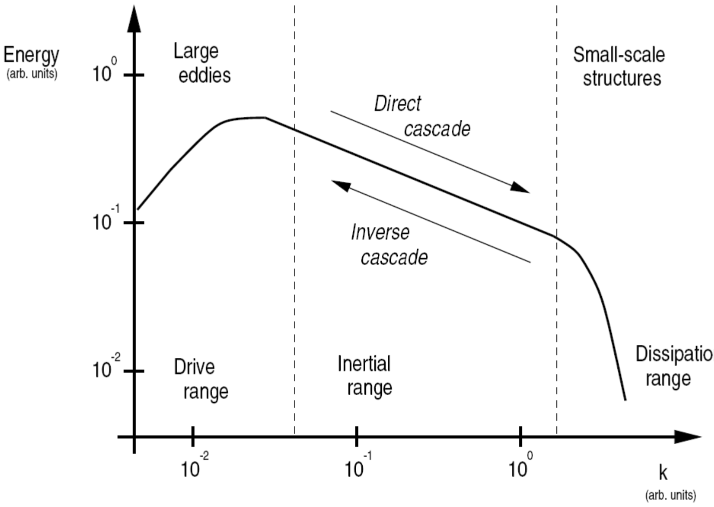

Figure 2.1: The Kolmogorov wave number spectrum of the kinetic energy of turbulence [28]. The X axis is not the k, wave number of sound, but the wave number of turbulence $\mathbf{k}_t$*, which is defined in* (2.4).

2.2 Measurement of noise

There are many measurable quantities and interactions behind the physical phenomena. Topography and obstacles, flow resistivities of surfaces, temperature, humidity, different wind components and lapse rate are the most evident measurable quantities. Horizontal and vertical wind components and turbulence parameters also belong to the most important factors. Both wind and lapse rate can change the sound wave propagation path and usually explain the fastest changes in time.

The occurrence of large fluctuations in the sound pressure field received from a source of constant strength is a remarkable phenomenon in outdoor sound propagation. These fluctuations are induced by atmospheric turbulence [26, 29]. Experimental studies [30–33] show that there are about 10 dB changes in short distances (less than 100 m). In longer distances, the fluctuations increase. Salomons et al. suggests that effects of turbulence on the time-averaged sound pressure level may be ignored if the source and the receiver are very close to the ground [29].

The lapse rate has effect on turbulence. If the temperature rises as a function of height, there is a positive temperature gradient and this meteorological situation is called as *inversion*. Upward oriented sound rays are bent towards ground during inversion. During inversion, scattering is decreased due to the maintaining mechanisms of turbulence die down. On the contrary, during negative temperature gradient the turbulence is usually strong.

This presentation is very simplified and only the most basic interactions have been shown (see also Fig. 2.4). Sound propagation in the atmosphere is affected also by many other factors and all these coincide more or less complex way, often changing rapidly as a function of time. However, using enough averaged measurement results, it is possible to evaluate sound propagation in different meteorological and acoustical conditions. One approach is to use a well-defined combination of a physical and a statistical model (see Sec. 2.3).

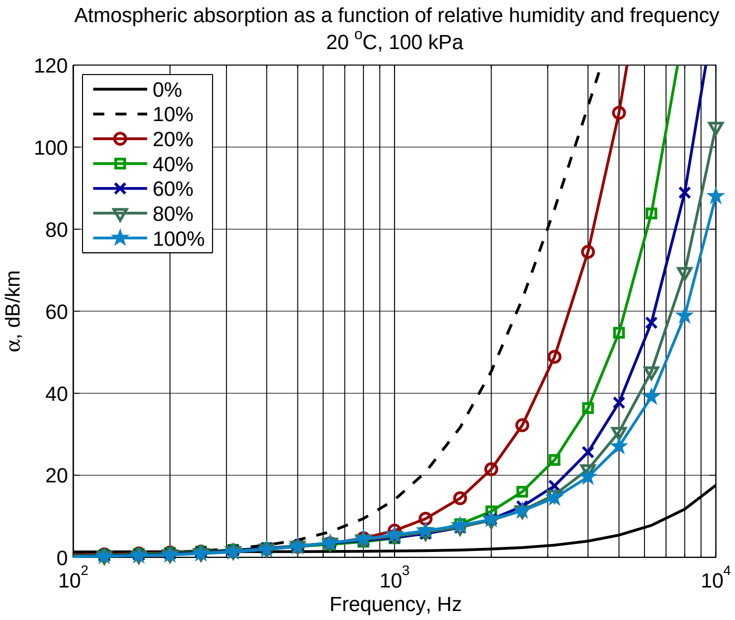

Figure 2.2: Atmospheric absorption along ISO 9613-1:1993 [34]. Sound is attenuated less while humidity increases, except for humidities below 10 % (see Fig. 2.3).

2.3 ATMOSAKU

A wave equation based sound propagation software was formerly developed at VTT. The ATMOSAKU software uses different parabolic equation (PE) simplifications to solve the wave equation. This hybrid software takes the topography, changing surface impedances, and numerous meteorological parameters into account. In addition to the physical part, the software contains a statistical module, which fixes the calculation results based on long-term sound propagation measurements and statistical analysis. The cover page figure showing noise emission from a 50 m high point source (e.g. a wind generator) in strong atmospheric inversion condition is calculated using ATMOSAKU.

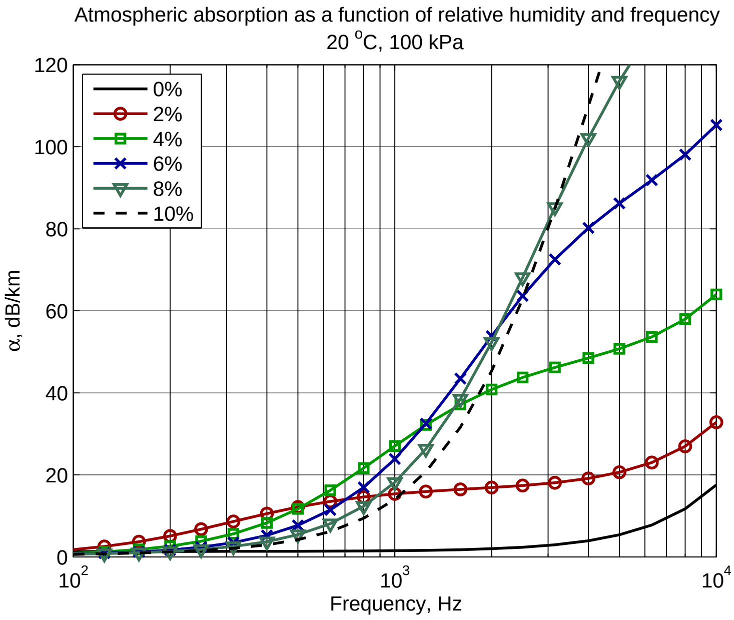

Figure 2.3: Atmospheric absorption along ISO 9613-1:1993 [34], for the range 0...10 %.

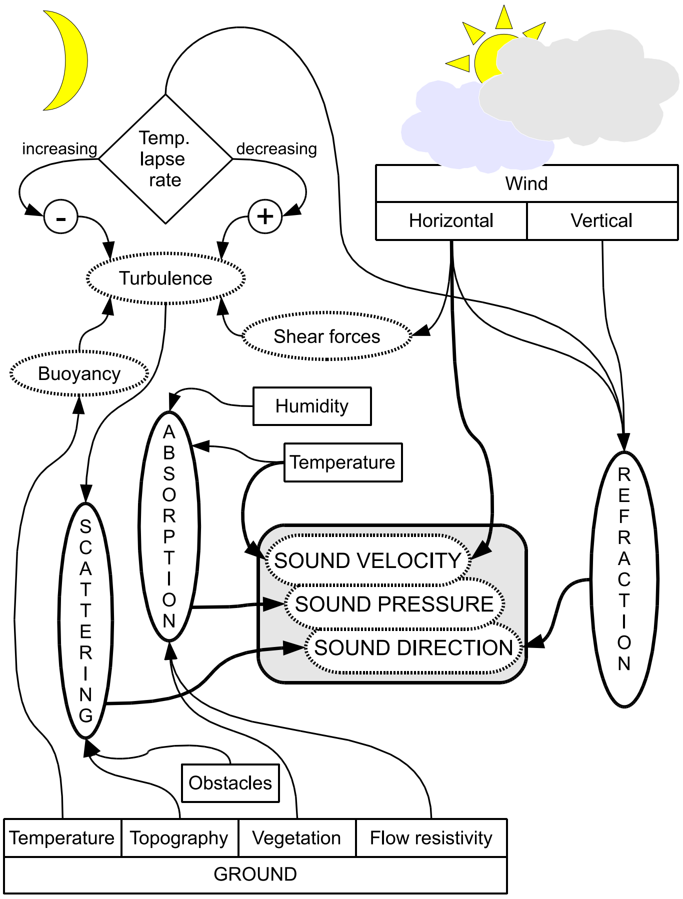

Figure 2.4: The most important factors and their interactions.

Chapter 3

Long-term measurements

There exists a big demand on well-defined sound propagation measurements. It is challenging to arrange data acquisition adequate for scientific purposes: tens of atmospheric and environmental factors should be monitored. Sound propagation is strongly affected by the weather conditions, but which are the most important factors?

Measurements are needed to develop new models, to evaluate the existing models, and maybe the most important, to evaluate environmental noise levels. However, only a few extended measurement campaigns are reported in the literature. There are a couple of long-term measurements [35–38] and quite extensive campaigns like the “Norwegian Trials” [39], where a lot of meteorological and acoustical data was captured during periods of days or weeks. Additionally, there exists a lot of long-term measurements, where only sound pressure levels have been captured at a distance from some noise source — the only use of these measurements is for local statistics. If there are variations — which is likely — they cannot be compared to anything due to lack of explaining data: what are the changes in noise source, environment, or meteorological conditions?

In this chapter, an overview for some remarkable measurements found from the literature is shown. There are some other known measurements just finished or still ongoing, but there are no papers available publicly, yet.

3.1 Japan, 1989–1990

A good example of a long-term measurement with insuccifient instrumentation was organized by the Japanese [35]. The Japanese measured during a 14 months period. The signal was emitted from a fixed point at an artificial island on the sea and received on the seacoast about 5 km from the source. The measurements were carried out at every hour and they found that propagation path could show variations of 20. . . 30 dB within half an hour in total sound pressure level. The maximum variations in one-day periods were found to be 50 dB or more. Further, daily variation patterns showed that noise reduction value is low at nighttime and high in the daytime from autumn to winter, but this cannot be seen in other seasons.

3.2 Norway, 1994–1996

The first serious, publicly reported, extensive measurement with proper meteorological characterization was organized in Norway [39]. These ”Norwegian Trials” consists of four large-scale outdoor sound propagation experiments from 1994 to 1996. During the field experiments, acoustical measurements were carried out in conjunction with meteorological, seismic and ground characterization measurements. Sound propagation was measured over distances from 0.1 to 24 km. The results were compared with different theoretical predictions. Unusual was that up to 30 m height microphone masts were used.

3.3 Finland, 2004–2005

The Finnish carried out carefully planned sound propagation measurements with extensive instrumentation during 2004–2005 [36]. About 100 environmental factors were measured once an hour simultaneously with the sound propagation measurement during a period of over 20 months. The vertical gradients of wind and temperature were determined using ultrasonic anemometers at different heights in a 50 m high meteorological tower, a SODAR [40] and by radiosonde soundings (up to height of 30 km). A loudspeaker emitted a well-known sound power pattern of static sinusoidals and a sweep and an 8 microphones antenna captured the signal at a 3.24 km distance. The calibrations of the source and microphones were checked every hour. The terrain was flat swamp with shallow vegetation. All these almost 15 000 measurements resulted a database with millions of files and terabytes of sound and environmental data. Some of the results were published in [41]. They found that at a distance of 3 km from the source, the attenuations were spread over a dynamic range of 80 dB. Comparison of excess attenuations[1] during different seasons was remarkable. In Fig. 3.1, excess attenuations during the quarters of the year are shown. The differences are about 10 dB between quarters. It is noticeable that higher frequencies (above 400 Hz) never had negative excess attenuation!

3.3.1 Most important explaining factors

The changes in excess attenuation are explained with quite traditional and sensible factors. As a conclusion based on correlation analysis with over 100 meteorological parameters, the *low frequencies* are affected mainly by *wind speed and different turbulence parameters*. For the *higher frequencies* the most important parameters are *humidity and temperature lapse rate*, but also *sensible heat flux* (QH) and longitudinal, transversal and vertical *turbulence intensities* explain excess attenuation significantly. These and some other factors explaining excess attenuation statistically significantly are listed in Table 3.1. The enhancing tendencies, i.e. excess attenuation increases while the factor value increases, are marked with a green color and an upward arrow while decreasing tendencies are marked with a red color and an downward arrow.

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[1] The excess attenuations presented here are the measured attenuations minus geometrical attenuations: a negative excess attenuation means that sound has attenuated less than would be expected using the 1/r law, possibly due inversion or down-wind.

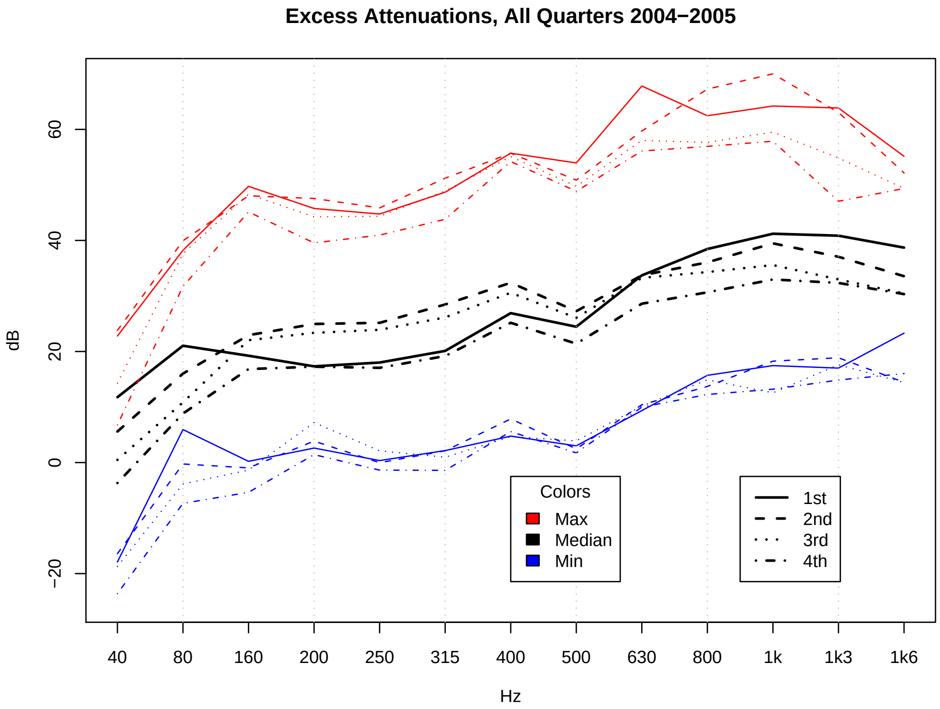

Figure 3.1: Excess attenuations and quarters of the year: Jan–Mar (1st), Apr–Jun (2nd), Jul–Sep (3rd), and Oct–Dec (4th). Distance 3 km from the source.

Table 3.1: Some statistically significant meteorological factors and their tendencies.

Hz	Factors
40	lwspda↓, lwspdmax↓, pasq↑, gradthgt↑, gradt↑, spress↑
80	lwspda↓, lwspdmax↓, icldness↓
160	lwspdmax↓, lwspda↓, pasq↑, spress↑, snowd↑, idewpt↓, tempc↓
200	mtr↑, mtq↑, ihum↓, gradthgt↓, tempc↑
250	ihum↓, gradt↓, gradthgt↓, mtq↑, tempc↑
315	gradt↓, ihum↓, tempc↑, gradthgt↓, mtq↑, mtr↑
400	gradt↓, ihum↓, gradthgt↓, tempc↑, mtr↑, mtq↑
500	gradthgt↓, gradt↓, ihum↓, tempc↑, mtr↑, mtq↑
630	gradt↓, ihum↓, mu↓, mv↑, mtr↑, lvdira↓
800	gradt↓, ihum↓, lvdira↓, mu↓, gradt↓, mv↑, mintc↓
1000	gradt↓, ihum↓, mtq↑, mhf↑, mtr↑, mtp↑, mintc↓
1250	gradt↓, ihum↓, mhf↑, mtr↑, gradthgt↓, mtq↑, lvdira↓
1600	mhf↑, mtr↑, ihum↓, mtq↑, mtp↑, mintc↓

gradt = temperature gradient
icldness = cloudiness
ihum = humidity
lwspda = local wind velocity 10 min avg
mhf = sensible heat flux
mtp = longitudinal turbulence intensity
mtr = vertical turbulence intensity
mv = vertical wind velocity
snowd = snow depth
tempc = surface temperature in Celsius
gradthgt = temperature gradient height
idewpt = dew point
lvdira = local wind direction average
lwspdmax = max wind velocity
mintc = minimum temperature, hgt 2 m
mtq = transversal turbulence intensity
mu = horizontal wind velocity
pasq = Pasquill index
spress = surface pressure

3.3.2 Correlations

Interesting differences can be found while comparing the correlations of excess attenuations between the low and high frequencies. Taking an average of correlations for frequencies above 1000 Hz as a function of frequency shows that these high frequency excess attenuations don't correlate very well with excess attenuations at low frequencies (Fig. 3.2). This is contrary to low frequencies. In other words, while high frequencies have been attenuated more, then low frequencies have not attenuated correspondingly. One explanation could be that there are some different effective factors in the atmosphere for the low and high frequencies.

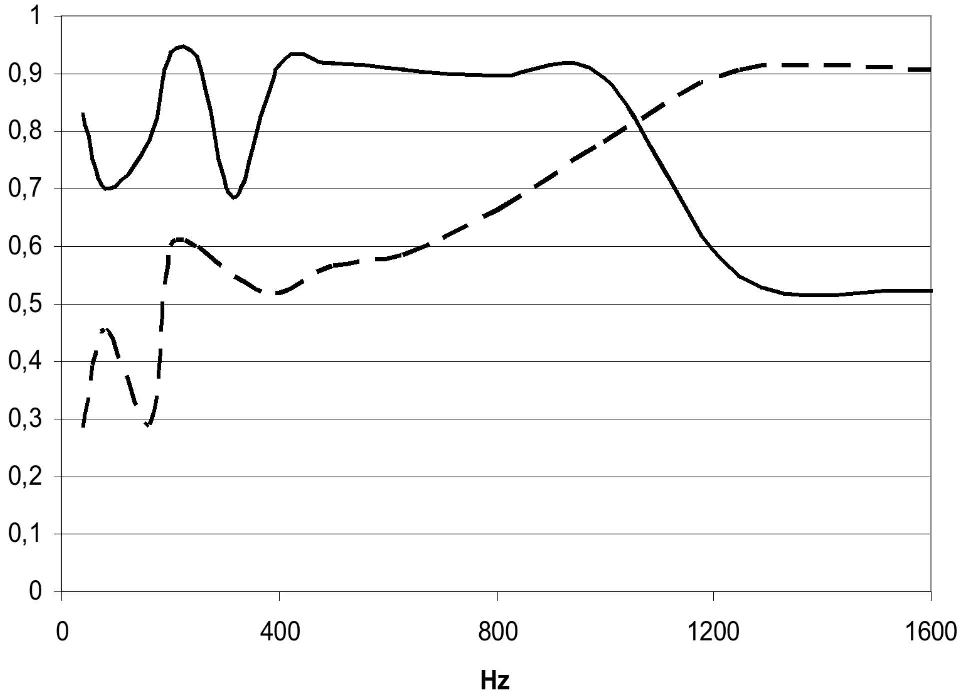

Figure 3.2: Correlations of the excess attenuations between high and low frequencies.

3.3.3 Excess attenuations versus time

It is well known that sound is attenuated more during the daytime. There are several physical phenomena explaining this, but what are their contributions? This is one of the questions for further analysis, but this effect was spectacularly clear in the Finnish study. In Fig. 3.3, average of excess attenuations at all frequencies during this campaign (over 20 months) is shown versus time of the day. There is a rapid increase of 10 dB in attenuation between 4 to 6 UTC and a slightly slower decrease towards evening. Variations are stronger in the daytime too.

Similar results can be found from the literature. Hole [42] used a mesoscale atmospheric model to simulate the break up of a morning air-temperature inversion during a clear weather situation with low wind speeds at ground.

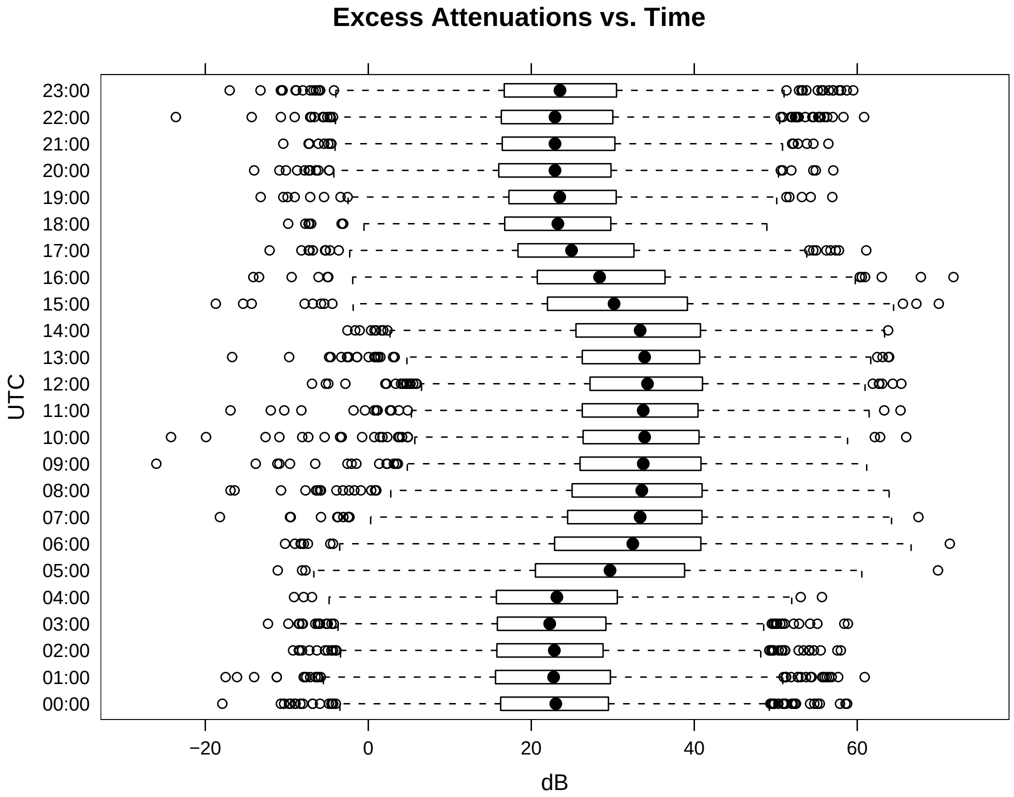

Figure 3.3: Excess attenuations versus time of the day (UTC time). Box contains 50% of the data and the black dot in the box indicates the median value. The whiskers are extended to a maximum of 1.5 times of the box width (or extremes) while there remain some outliers indicated by rings.

3.3.4 Pasquill stability classes

There are many methods of categorizing the stability of a region of the atmosphere. Pasquill stability classes [43] are designed to provide semi quantitative measures of the mixing capabilities of the lower atmosphere in terms of the horizontal surface wind, the amount of solar radiation (sun incidence angle), and the fractional cloud cover (ceiling). Low values (Classes A=1, B=2 and C=3) indicate that the atmosphere is unstable and sound scattering due thermal turbulence and convection is strong. The most frequently occurring class is D, equal to number 4, indicate that the atmosphere is neutral, with possible weak, sporadic buoyancy but often a windy day or night, which causes scattering providing mechanical turbulence. High values (Classes E=5 and F=6) indicate that the atmosphere is stable and buoyant forces are weak. Class A is very unstable and corresponds to hot, calm days while class F is very stable and corresponds to nights with low winds.

The excess attenuation data was analyzed versus calculated Pasquill classes and a statistically very significant*** dependency was found (Fig. 3.4). An unstable atmosphere indicates a strong attenuation while a stable atmosphere indicates almost 20 dB lesser attenuation. Windy days with neutral atmosphere cause the range of excess attenuations spread to a wide range of values while the calm days with strong unstable atmosphere cause less variation to the values of attenuations.

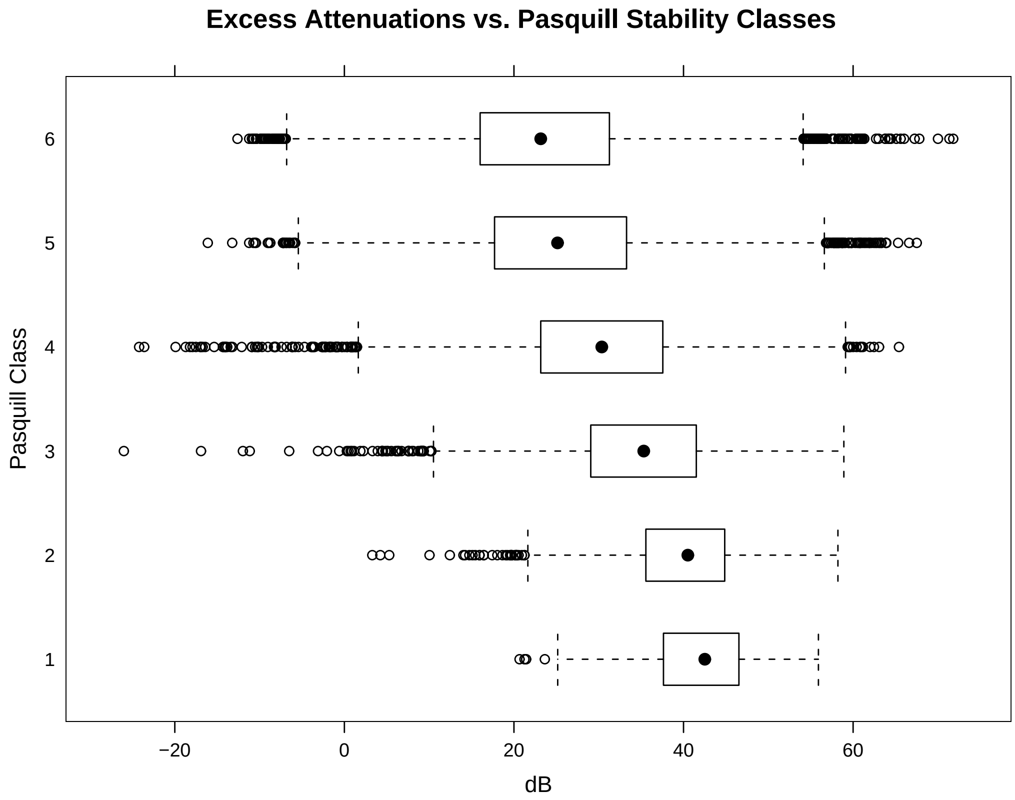

Figure 3.4: Excess attenuations versus Pasquill stability classes. The symbols are equal to Fig. 3.3.

3.4 Harmonoise–project

One of the objectives of the European Harmonoise project was to develop noise propagation models to be used in member states for noise mapping. The Harmonoise models (Engineering model [44] and Reference model [37]) suggest many meteorological measures to be taken into account. Some long-term measurements were made to validate the models.

Chapter 4

Uncertainties

Knowledge of the *reliability* of the mappings and predictions is a key to well informed decision making. Wilson and Pettit propose the use of special expert decision support tools (DSTs) [45] in characterizing the effects of the terrain and atmospheric conditions on sound propagation. The DSTs expose both the possible problems with the model and also if the source data is sufficient for reliable predictions.

Scientists usually refer to words reliability and *validity* [46–48]. *Inner reliability* measures if we can repeat the test and get the same result, and *outer reliability* rates if some other can repeat the test in another situation and get the same result. Validity is determined by how well the test is measuring what it is meant to measure. *Inner validity* shows if the performed test is done as it was documented and the test is valid externally (*outer validity*) if also other scientists understand the test and results as documented.

The reliability and validity can also be explained by *uncertainties*, *accuracy*, and *precision*. Probst says [49]: ”Accuracy of a calculation method describes the deviation of calculated results from the values obtained by an ideal measurement. An ideal measurement is characterized by negligible uncertainties. Precision of a calculation method describes the differences between results, that are obtained if different experts apply the calculation method in exactly the same case. Transparency is an expression for the ability to understand and to retrace calculations in each step. ” However, using the definitions above, we can say that accuracy corresponds to inner validity, precision to outer reliability, and transparency to outer validity. All these definitions can be covered using the word uncertainties. The uncertainties can be divided to sub-categories like *aleatory uncertainties*, resulting for example from random signal generation and scattering effects, and *epistemic uncertainties*, linked to the environmental state [45].

No one have seriously questioned the uncertainties of results until last years. In the days of the scale models, it was evident that computer models were imperfect [50], but today surprisingly many of the experts believe the uncertainties in noise mapping can be handled without unpleasant and laborious real measurements. The most popular way to study uncertainties has been comparing different models to each other [14, 51]. Another level of uncertainties appear, if the calculated results are compared to human responses [52]. An increasing amount of studies on the uncertainties have appeared during the last years [45, 53], including comparisons to long-term measurements [54].

Table 4.1: Some environmental measures and their best fitting equations. The abbreviations of the measures are explained in Table 3.1. This table is based on results from [55].

Chosen measure	Chosen model (some statistics and explained factor)
gradt	QUA (r^2 .807, p value .003, F value 14.67, x1600ch2)
gradthgt	QUA (r^2 .528, p value .072, F value 3.91, x500ch2)
ihum	CUB (r^2 .226, p value .000, F value 10.06, x500ch1)
mhf	CUB (r^2 .273, p value .000, F value 11.04, x800ch2)
snowd	CUB (r^2 .307, p value .000, F value 12.97, x80ch2)
tempc	CUB (r^2 .196, p value .002, F value 5.51, x1600ch2)
mtq	CUB (r^2 .192, p value .000, F value 6.96, x1250ch1)
pasq	INV (r^2 .140, p value .001, F value 12.23, x500ch1)
spress	CUB (r^2 .048, p value .186, F value 1.72, x160ch1)

4.1 One approach to deal with uncertainties

It is possible to do very carefully prepared acoustical measurements of sound propagation. Using a well-known sound power source with a known radiation pattern, calibrated microphones, and extensive instrumentation in the environment. Correlations between the changes in the acoustical signals captured by the microphones and changes in the environmental quantities can be found. Some basic and advanced statistical methods can be used to select the most important factors. The dependencies can be very strong and statistically very significant, which means the changes in environmental conditions explain the changes in noise levels.

Pasquill index (see Sec. 3.3.4) is a good example: unstable atmosphere cause less variation which predicts less uncertainties while neutral atmosphere indicates very high uncertainties to the results [55].

A more advanced approach is to find the most important measures and their combinations. In the situation of inversion there is no turbulence and lapse rate is the key measure. In neutral and stable conditions the wind profile and turbulence measures are essential. When these key factors are discovered, different equations, e.g. linear (LIN), logarithmic (LOG), inverse (INV), cubic (CUB), quadratic (QUA), and so on, can be tried to the factors to choose the best fit by different statistical means (see Table 4.1). Then nonlinear regression analysis can be applied to form equations which give the expected uncertainties as numerical values.

The implemented ATMOSAKU statistical model tries different combinations of available environmental parameters to find the best fit for an error curve and calculates an estimate for the uncertainty (see Table 4.2).

Table 4.2: A demonstrating test run for a case of 150 Hz where the physical model gives attenuation -14.9 *dB and the statistical model gives* ± 1.9 *dB could look like the following:*

```
* Now we engage the statistical model *
Frequency/frequencies 150 300 600 Hz were asked.
Statistical model selects the closest frequency for each
estimate
so equivalent frequency/frequencies are 160 315 630 Hz.
NOTE! Physical model calculates using exact frequencies!
Trying following factors for the frequency 160 Hz:
+constant (+3.64e+01 dB)
+mhf (+1.27e-01 dB)
+itempc (-8.43e+00 dB)
+ivisibp3 (-2.33e-01 dB)
+mustar (-5.28e+00 dB)
Trying following factors for the frequency 160 Hz:
+constant (+3.64e+01 dB)
+mhf (+4.29e-01 dB)
+itempc (-5.17e+00 dB)
+ivisibp3 (-4.40e-01 dB)
+mustar (-4.23e+00 dB)
+iwspd (-3.49e+01 dB)
+ihump2 (-5.29e+00 dB)
-> Xatten for 160 Hz is -14.9+-1.9 dB.
```

Chapter 5

Summary

There are dozens of user friendly tools available for environmental noise mapping. Most of the engineering level tools are based on ray tracing based, internationally standardized techniques or national standards. Currently these software, however, don't give satisfactory results with wind power plants as noise sources. The software algorithms neglect many essential phenomena characteristic to windmills.

More advanced, scientific models, which solve or approximate the full wave equation, can be applied to transfer path problematics of wind power plants. All the known environmental or meteorological phenomena can be taken into account with this class of algorithms.

Turbulence is proven to be the field of difficulties. Turbulence causes sound scattering, which can be the most significant source of changes in noise levels. The existing scattering theories are not defined with the properties of the real world atmospheric turbulence, which makes them perform poorly.

There are no explicit answers to the uncertainties of the noise mappings. The height of the noise sources in the windmills makes them disposed to more uncertainties. One approach is to utilize extensive long-term measurements and statistical analysis to form equations which give the expected uncertainties as numerical values. This approach can be applied to short-term measurements too. When the environmental key factors are measured along with the noise levels, an estimate of the expected variance of the noise levels can be calculated. One of the key factors is atmospheric stability, which can be approximated using Pasquill index. In unstable atmosphere less variation is expected while neutral atmosphere increases the level of uncertainties.

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