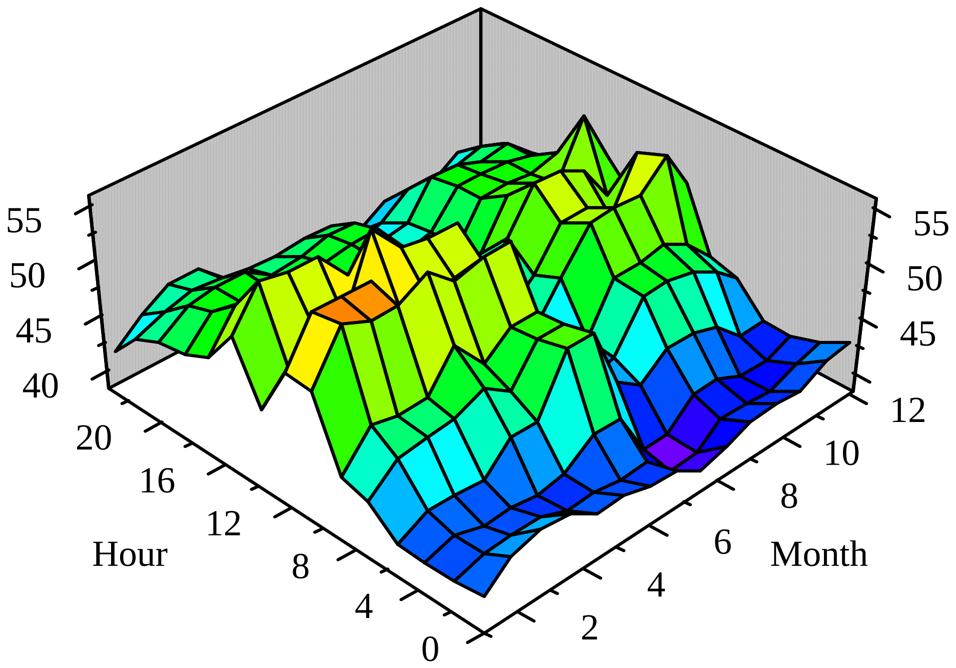
INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

58th IEA Topical Expert Meeting

Sound Propagation Models and Validation

Royal Inst of Technology, Stockholm, Sweden
Organised by: Vattenfall



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For more information about IEA Wind see www.ieawind.org

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IEA RD&D Wind Task 11

Topical Expert Meeting #58

Sound Propagation Models and Validation

Different approaches on noise limits
Sabine Schulz

This presentation is not included in the proceedings.

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A critical look at the wind turbine noise regime in Norway

sigurd.solberg@kilde.no

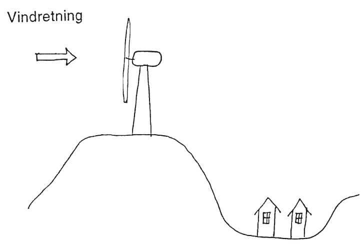
5-6. may 2009

iea wind

kilde

Recommended noise limits

Wind at the receiver	L_{den} (dB)
Sheltered (> 30% of the year)	45
Non-sheltered	50



Practical regime

1. Reference: 8 m/s at h=10 m
2. 80% operation

→ $L_{den} = L_{ref} + 5$ dB

3. Downwind
4. Prevailing wind

→ Tested calculation method ?

2-3 dB less strict assessment.

5. Sheltered receiver? → Method for assessment?

6. Show sensitive buildings $L_{den} > 40$ dB → How to use the information?

The typical situation

On-shore wind parks:

1.30-100 turbines in coastal (or montaineous) areas

2.Only small areas are wind- shielded → Limit: L_{den}=50 dB, L_{ref}=45 dB

3.Minimum distance turbine-building = 700-1000 m
Some holiday homes within the park.

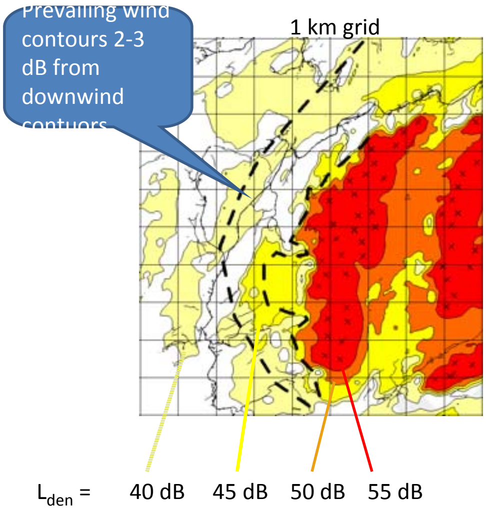
4.Remedial action:
- redemption (pay out)
- rearrange/remove turbines

Shadow sone at prevailing wind

Significant shadow: > 1 km
(Imagine P2P)

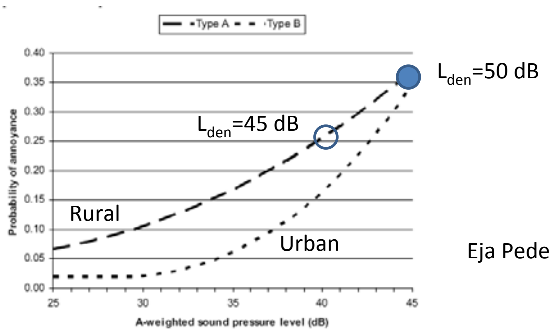
Pravailing wind contours should Be shown for L_{den} = 40 dB and 45 dB only.

Typical recommended noise limitit is L_{den} = 50 dB



Paradox 1:
below recom.limit

Annoyance score



Eja Pedersen, 2007.

(Frits van den Berg, et al. 2008)

Paradox 2:
high annoyance

3 possible regimes

Simple, with safety margins: Use downwind calculation only.

Seek significant differences:
- Assess the uncertainty in the calculations
- Do more favourable assessment in the case of clear differences only.

Comprehensive, new basis:
- Assess the annoyance studies,
- Investigate background noise in a selection of terrain types.
- Develop a method for terrain shielding assessment,
- Select a better founded recommended noise level and
- Test wind type differences by statistical significance.

Measuring and calculating turbine noise immission in the Netherlands

IEA Wind Expert Meeting Sound Propagation models
May 5th, 2009

Seppe Hoogzaad

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Content

- Background / present method used in Netherlands
- Why a new modeling method is needed
- Background information
- Possible adjustments to measuring method
- Possible adjustments to modeling method

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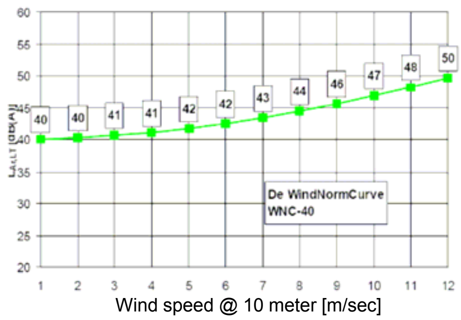
Present model used

1999: directions “HMRI-1999” (modeling derived from ISO 9613)
- Measuring in accordance with IEC 1400-11

2001: AMvB 487 (Dutch regulation)
- Normation curve issued (WNC-40) for background noise
- Measuring in accordance with IEC 61400-11



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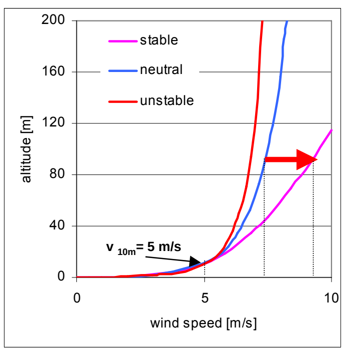
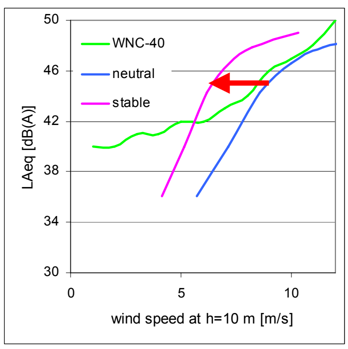
Why a new model is needed

2002-2006: Research from RUG “v.d. Berg-effect”





- At stable meteo conditions (night time) relatively higher wind speed at higher altitude (~100 m)

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Boundaries of new model

New:

- Use of L_{den} instead of $L_{Ar,LT}$ (new normation going to be in L_{den})
- Use of local meteo statistics at turbine axis height in combination with wind speed dependent sound power

Preserve the current modeling (HMRI'99) method as much as possible

Still undetermined boundaries:

- Model used for horizontal (HAWT) and vertical axis turbine (VAWT)?
- Model used of turbines larger than …?

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Mechanical sound

Modern turbines produce less mechanical sound than aerodynamic sound.

Therefore focus on aerodynamic sound.

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Aerodynamic sound (1)

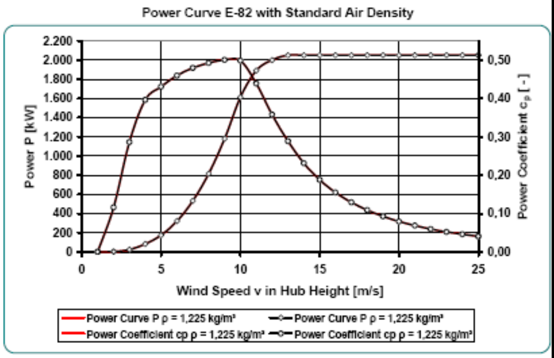
Aerodynamic sound caused by:
- Trailing edge turbulence
- Turbulence in boundary layer (stall)
- Turbulence at the tip (tip vortex)
- Turbulence caused by irregularities in the blade
- Interaction between blade and tower
- Inflow turbulence

Aerodynamic sound (2)

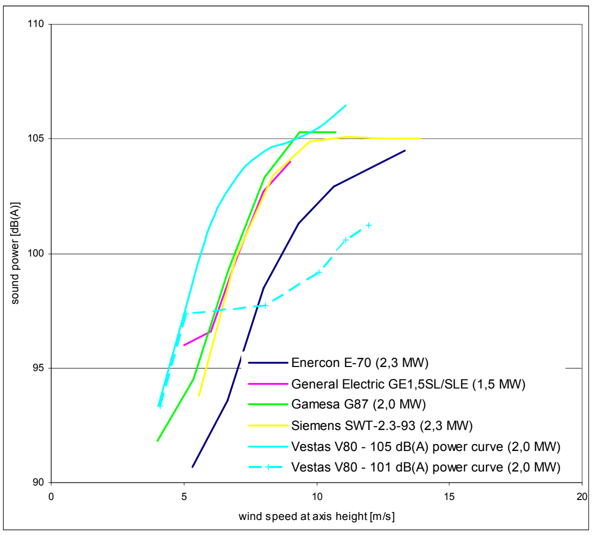
Characteristics
- Sound power proportional with 50log*v*
- Broad band emission
- Possible dipole- or quadripole emission

Power curve of turbine

- Relation between wind speed at axis height and generated electrical power
- Defines:
  - v_{ci},
  - v_{rated}
  - v_{co}
- Can be used to derive the wind speed at axis height.



Relation between sound power and wind speed



Possible adjustment for measuring sound power

- Define wind speed at axis height (instead of at 10 m)
- Use more measurement at more wind speeds, for example 4,5,6,…..,12 m/s at axis height
- Measuring of directivity of sound or use a defined directivity

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Distribution of wind in the Netherlands

- 50% of the time wind originates from the ZW ±60°
- 75% of the wind energy originates from the ZW ±60°

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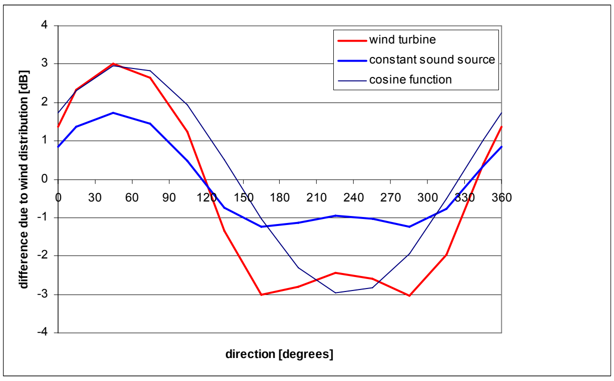
Distribution of wind in the Netherlands

illustration of sound immisson effect under following wind conditions at great distance from the source



X-axis: orientation of sound source – receiver point in degrees (0=North)

(at great distance form the source, sound immision during opposing wind condition can be neglected)

Sound sources at high altitude

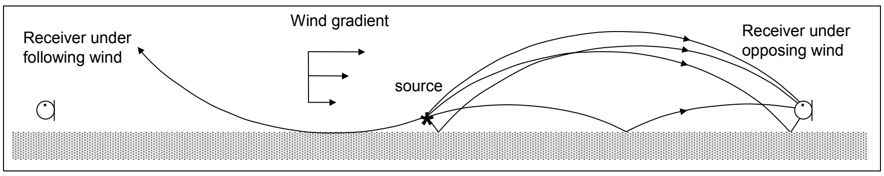
Wind gradient causes sound radiation bending and influents sound immision at great distance:

For low sound sources

- Wind gradient approximately constant

For high sound sources

- Wind gradient strongly depends on meteo



Directivity of turbines

- Trailing edge turbulence: dipole effects
- Measured: sound immission in direction of the axis about 3 dB higher than perpendicular to the axis
- Depends on the wind direction
- Independent of distance to the turbine

Overview of the three effects

- The local distribution of wind direction and speed causes different sound immision at great distance from the turbine
  - estimated effect in surroundings: ±3 dB
- Due to small wind gradient speed (under unstable conditions), the sound rays are curved less and are shielded less by the ground at great distance
  - estimated effect in surroundings: +2 dB ?
- Due to dipole effect of the sound radiated by the turbine, the sound immission is less perpendicular to the axis
  - estimated effect in surroundings: ± 2 dB

Possible adjustment for C_m

normal $r \leq 10(h_b+h_o)$

$C_m = 0$

suggestion

$C_{m,WT} = C_{m,dipool}$ (*)

normal $r \geq 10(h_b+h_o)$

$$C_m = 5\left[1 - 10\left(\frac{h_b + h_0}{r}\right)\right]$$

suggestion

$$C_{m,WT} = 5\left[1 - 10\left(\frac{h_b + h_o}{r}\right)\right] + C_{m,dipool}(*) + C_{m,\,as.\,windroos}(**)$$

$h_b \neq H_{axis}$? (correction for wind gradient under unstable conditions and/or big sound source of turbine

(*) possible function of cos(α-45)

(**) possible function of cos(α-45), dependent of distance r

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Questions?

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Wind Turbine Sound Issues in Finland

Carlo Di Napoli
Pöyry Energy Oy, Finland

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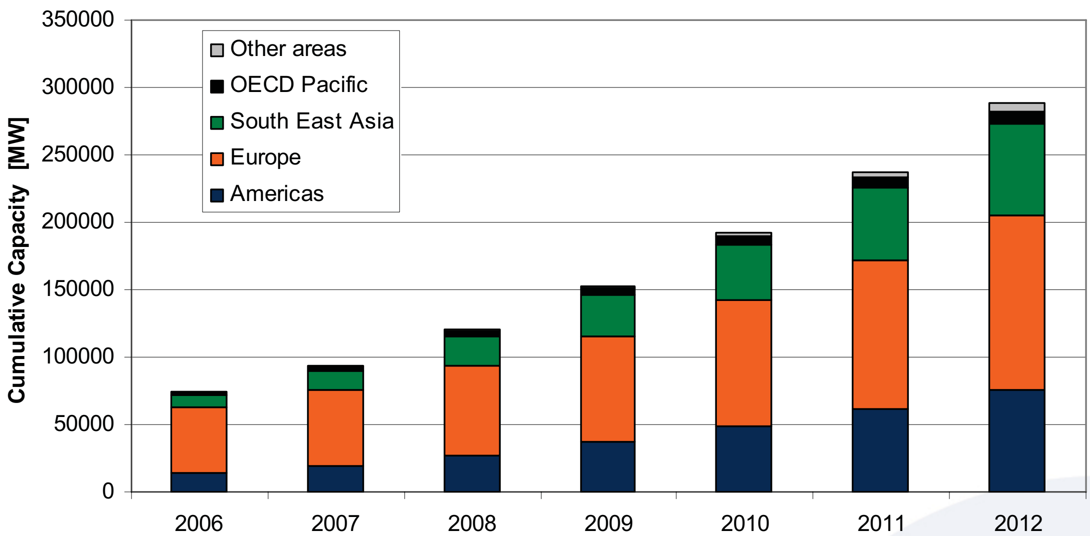
- Emerging Business
- Pulp & Paper Industry
- Chemical Process Industry
- Transportation
- Water & Environment
- Construction Services

Global trends driving the growth of wind energy

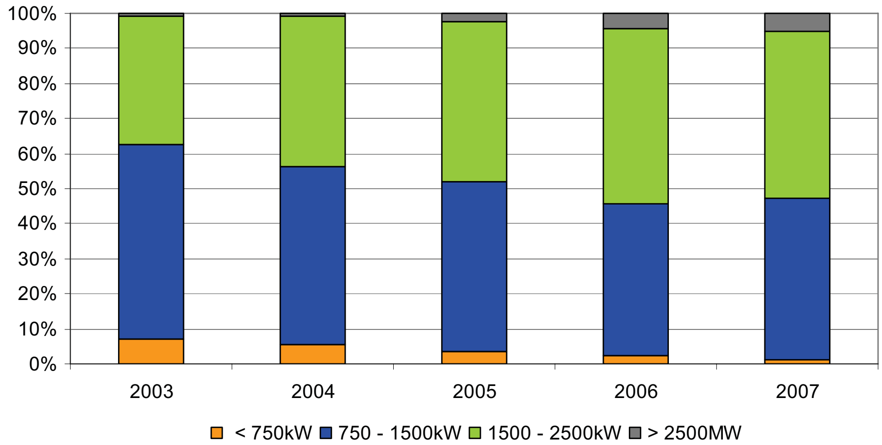
- National renewable energy targets
- Lack of other energy or renewable energy sources
- Growing importance of security of energy supply
- Increasing volatility of fossil fuel prices
- Overall awareness on environmental issues
- Employment and local development
- Improving cost competitiveness
- Technology development

Expected global growth of wind power capacity



Source: BTM World Market Update

Wind Turbine size



- **The most popular turbine size today is 1-2MW**
- **3MW size most efficient in forested and populated areas**
- **Different size turbines for different markets**
- **5 to 6MW turbines in operation already, but in small series**
- **7 to 10MW turbines on drawing boards**
- **Manufacturers focusing on large series**

Source: BTM World Market Update

Country Profile - Finland

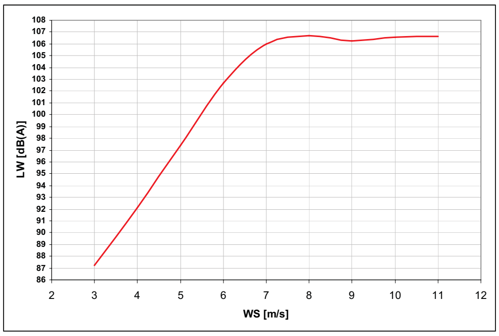
- Finland has many potential wind turbine sites with water ”between” two onshore sites
  - 5.3 Million Inhabitants
  - About 76 000 islands
  - 56 000 lakes
  - 314 000 km of shore line
  - 465 000 Summer Cottages (85% close to shore line) => 40 dB(A) night time noise limit for recreational areas
- National Wind Atlas ready at the end of this year (2009)
- Wind power projects still very small => about 200MW of installed capacity so far, many projects with only 1-5 installed turbines, some close (< 1km) to summer cottages
- New project plans > 2000MW of capacity within next 10 years => the ” big rally” is just about to start (waiting the national fare system/guaranteed price for wind power in 2010 or 2011)
- Large size project EIA’s are under way

Wind Turbine as a Sound Source

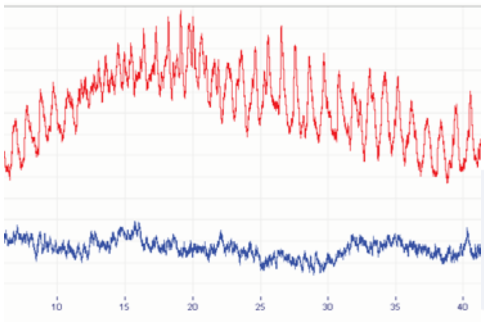
- Amplitude Modulated Aerodynamic Sound ("AM Noise")
- Pitch Regulated Turbines Lw highly dependent on wind speed (rotational/blade length dependency)
- Potential for Structure Borne Sounds (Long and Hollow Tower)
- Occurrence of Blade Rotation Synchronizations (Wind Parks)
- Many Types of Aerodynamic Noises (basic "Whoosh", whistles, "jet sounds", etc.)
- <u>Overall Source Level and Propagation have High Dependency on Environmental Conditions</u>
  - Wind Speed (Lw)
  - Wind Direction => Propagation path, Directivity
  - Changes in Overall Weather (RH%, wind speed, T) => Changes in Sound Attenuation
  - Night Time Atmospheric Stability => Wind Profile + Turbulence change => Changes in Angle of Attack (Pulsating Sounds) + BG-sounds + Sound Attenuation

Wind Turbine as a Sound Source

- Sound Power Level dependency on wind speed (@ 10m height)
  - Sharp increase of sound level @ lower wind speeds (almost 5 dB/ m/s!)
  - Same change can be seen in some immission points (especially during low BG-sounds =>night time)



- AM Noise
  - Pulsation height can be 5-6 dB with 1 turbine
  - Pulsation Strength vs. Environmental State
  - Rapid immission level changes possible
  - Occurrence of Synchronization with wind parks => increase of pulsation strength



Sound Propagation Models in Finland

- No Specific National modelling or measurement rules for wind turbine noise exist (yet)
  - Regional Environmental Centres ”Rely” on Consultants Know How
- Simple and old guidelines for immission level measurement (mainly traffic noise and static industrial noise sources)
- Old Nordic Model (DAL32) is still used in most of the EIA Projects (excluding EU level noise mapping for large cities) => Reliable results in most standard industrial and traffic noise cases
- Short Assessment Report of Wind Turbine Noise (situation in 2006) in Finnish Language (Di Napoli)

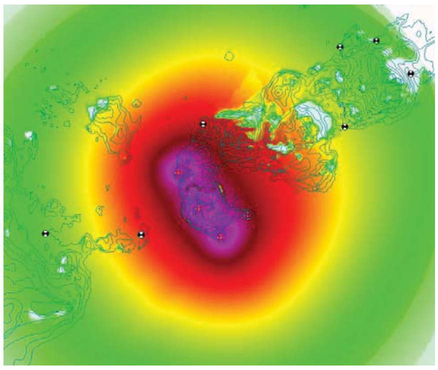
- Old Swedish Sound Propagation Rules for Offshore Projects Created lot of Criticism Among the Wind Turbine Project Developers => estimated sound levels considered to be a lot higher than ”real” situation

Sound Propagation Models – Current Situation

- Done in every EIA phase => Environmental Centres do prefer GIS based 3D sound propagation maps with colour
- Terrain typically modelled well with modern commercial point-to-point programs (ground abs =0, “worst case”)
  - problems of estimating special weather conditions (inversion, downwind conditions)
  - many estimations based on ”given” values by developers => lack of true experience on complex wind turbine sound => summary of the L_{Aeq} sound levels only
- Weather correction possible with wind rose data (some basic instructions also given by the Ministry of Env.)
- Small projects with only few turbines not necessarily addressed to EIA process at all => simple estimation (or just guessing) of noise level at immission points => errors more possible

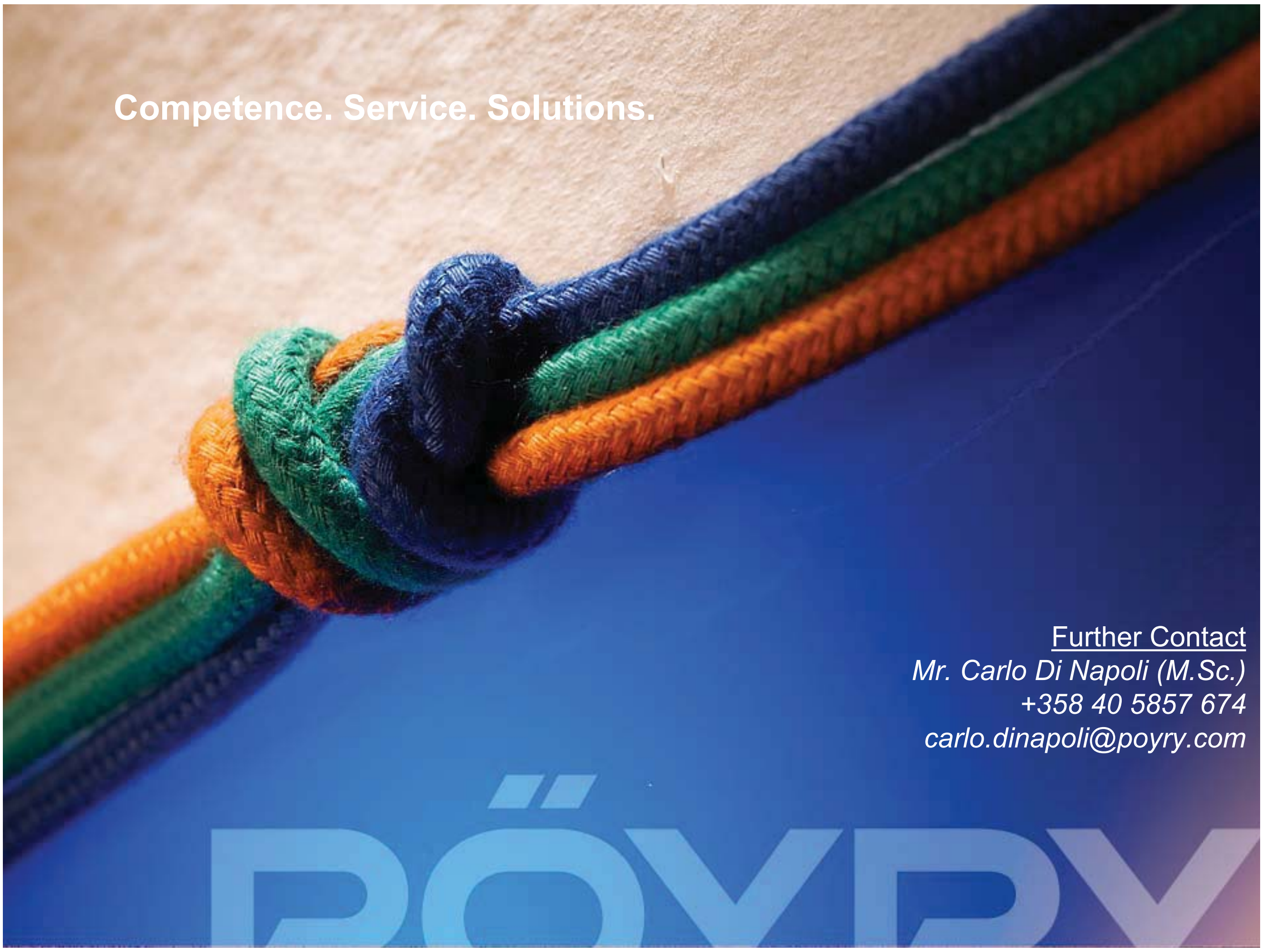
Sound Propagation Models – Risks of Wrong Conclusions

- The Strict Interpretation of Given Environmental Permit (”EP”)
  - If Immission levels are exceeded several times the given noise limits (after the wind park delivery, measured values), legally examined the Wind Park Owner is in an illegal position against the Authority and National Environmental Law. => Rapid Demands from Authority for reduction of noise levels
  - Changing weather conditions may create a business risk to the Owner, if EP noise limits are truly exceeded
  - Pressure to EIA authors



Sound Propagation Models – Future Needs

- Development of National Rules for Wind Turbine Sound Models and Immission Measurement Practices
  - On-Shore, Near-Shore, Off-Shore
- Background sounds? Many areas have <30 dB(A) BG’s during night time => the true loudness of AM sounds?
- Development of <u>Specific Measurement Rules</u> (windy conditions totally opposite than typical instructions of weather conditions for immission level measurements at the moment)
    - Wind Park Project Delivery/Acceptance Phase:
      - Possible Guarantee Tests (IEC 61400-11 + Immission Points)
    - Immission Tests after Noise Complaints!
  - Harmonization of ”results” (interpretations)
    - Reliability (true ”nature” of WTN)
    - Transparency (yet still ”easy-to-comment”)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PÖYRY

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Wind Farms Noise

Brief Overview of Assessment and Prediction Methodology in the UK

Rob Shepherd
Hayes McKenzie Partnership Ltd
Salisbury & Machynlleth

General Noise Assessment

- Compare predicted noise levels with:
  - Pre-existing level of specific noise (not valid for new development).
  - Absolute limit (used for noise from transport, construction, minerals).
  - Pre-existing background (used for noise from industrial sources).
- Noise from wind turbine sites
  - Guidance for industrial sources suggests comparison with 'background'.
  - Lack of guidance for low noise environments (e.g.. Scope of BS4142)
  - Specific requirements for wind farms led to hybrid proposal (ETSU-R-97).
  - Takes into account variation in source noise and background with wind.
  - Relates to 'worst case' wind direction.

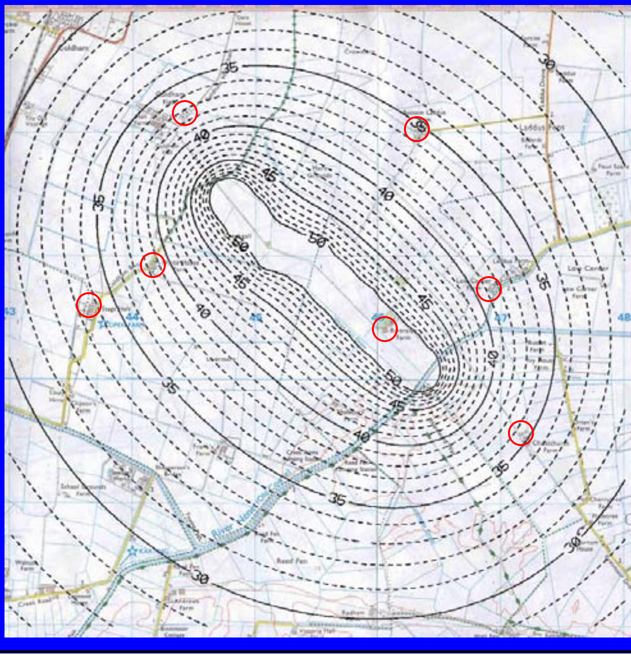
ETSU-R-97 Noise Limits

- X dB L_{A90} or 5 dB above 'prevailing' background, whichever is the greater.
  - X varies with time of day and other factors
    - Day-time: X=35-40
    - Night-time: X=43
    - Financially Involved: X=45
  - B/G quantified as a function of wind speed
  - B/G averaged over relevant period
    - night 2300-0700
    - 'sensitive' day-time hours (1800-2300, Sat pm and all day Sun)
- Simplified Limit 35 dB L_{A90} for V_{10} < 10m/s

Noise Planning Limits

- Noise limits are set relative to background therefore:
  - Background measurements must be robust, but are always open to a great deal of scrutiny
  - Background noise varies with e.g.
    - Exact microphone location
    - Variation e.g. with time of year etc.

Measurement Locations



Wind Speed

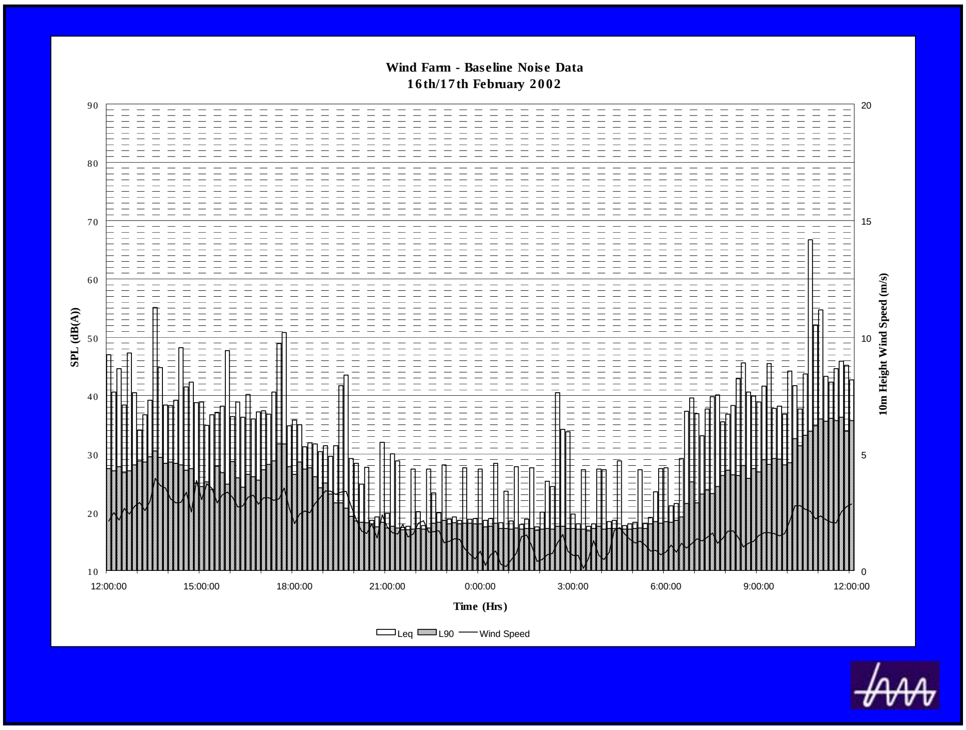
Wind speed is measured on-site, time synchronised to noise measurements.

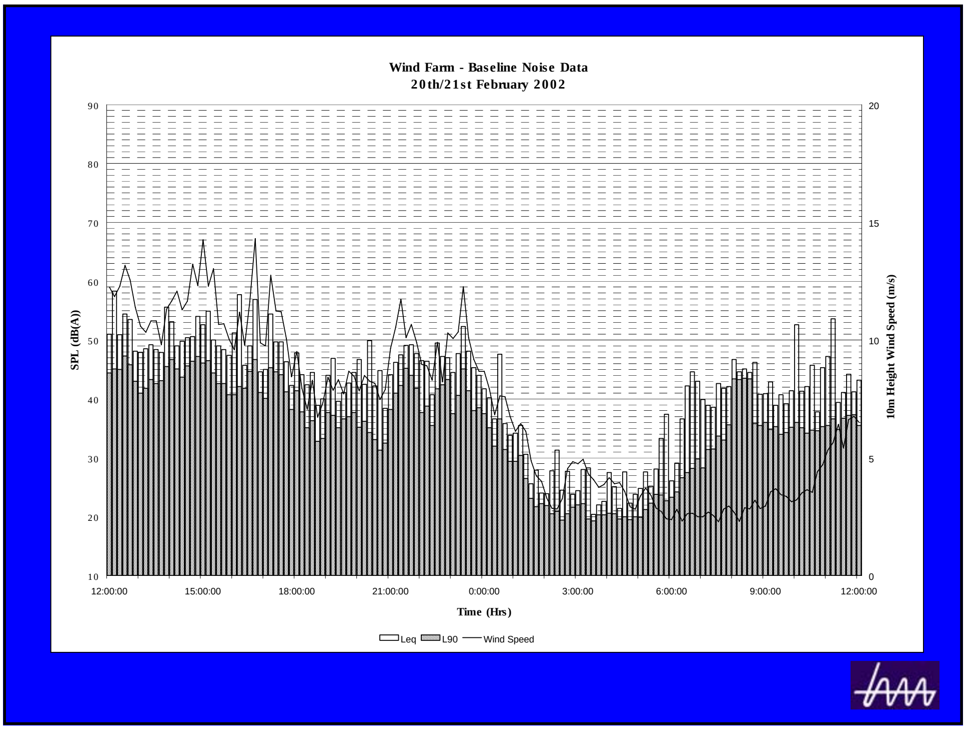
Measurements specified in ETSU to be carried out at 10m height. However it is impossible to estimate hub height wind speed with any accuracy from 10m height measurements alone.

Wind Shear

- Speed up from reference height (10m) to hub height may be greater than predicted from ground conditions alone.
- A modification to the ETSU-R-97 methodology has been agreed such that baseline measurements are referenced to measured or ‘accurately’ derived hub height wind speeds.
- Wind speed for baseline noise and source noise are then corrected to ‘standardised’ 10m height.

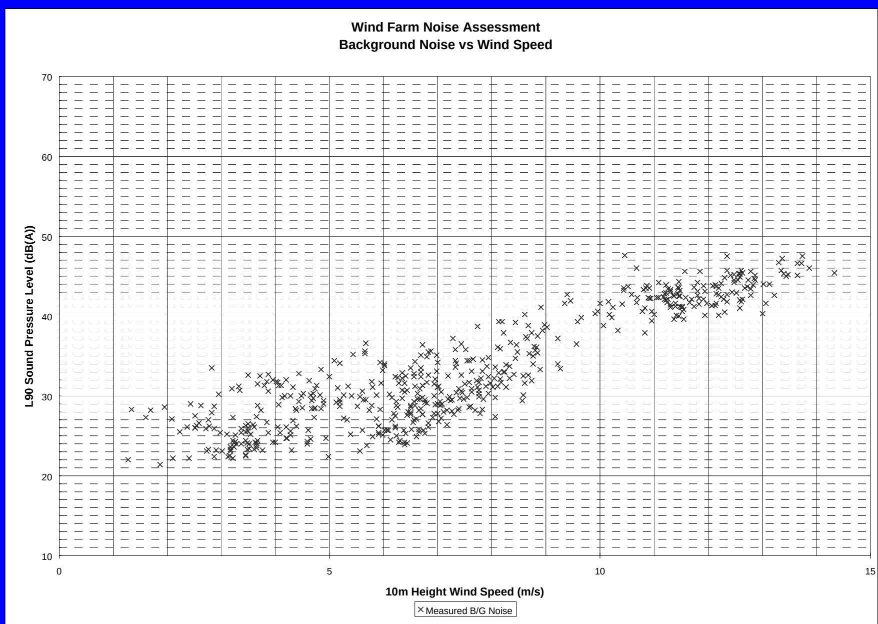
Siting

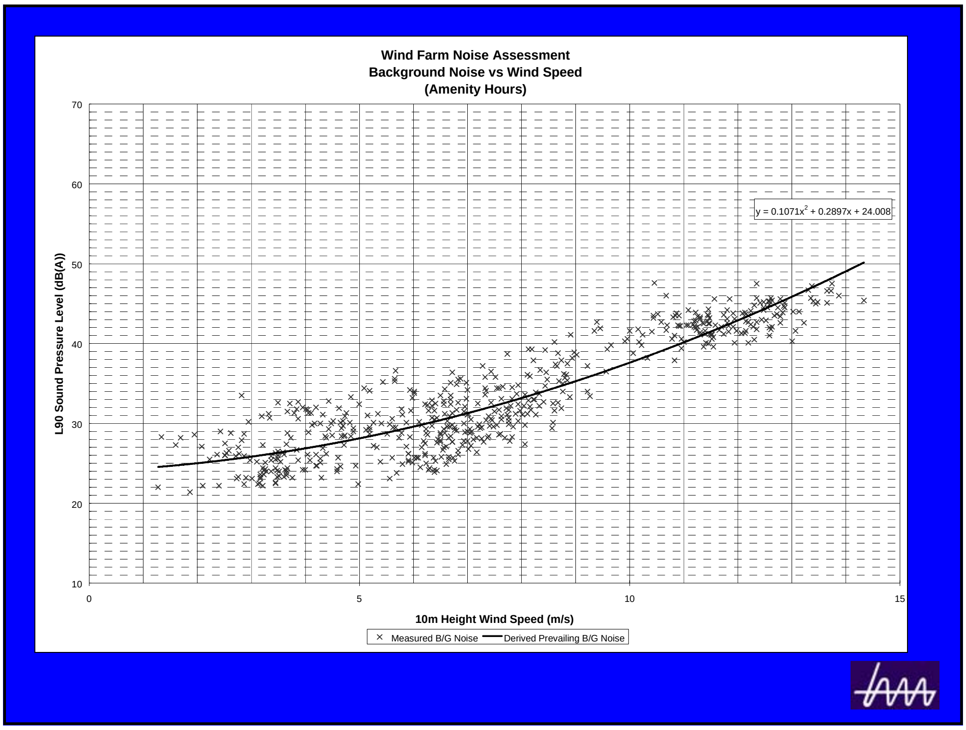

Wind Farm - Baseline Noise Data
16th/17th February 2002
SPL (dB(A))
10m Height Wind Speed (m/s)
Time (Hrs)
12:00:00
15:00:00
18:00:00
21:00:00
0:00:00
3:00:00
6:00:00
9:00:00
12:00:00
Leq
L90
Wind Speed

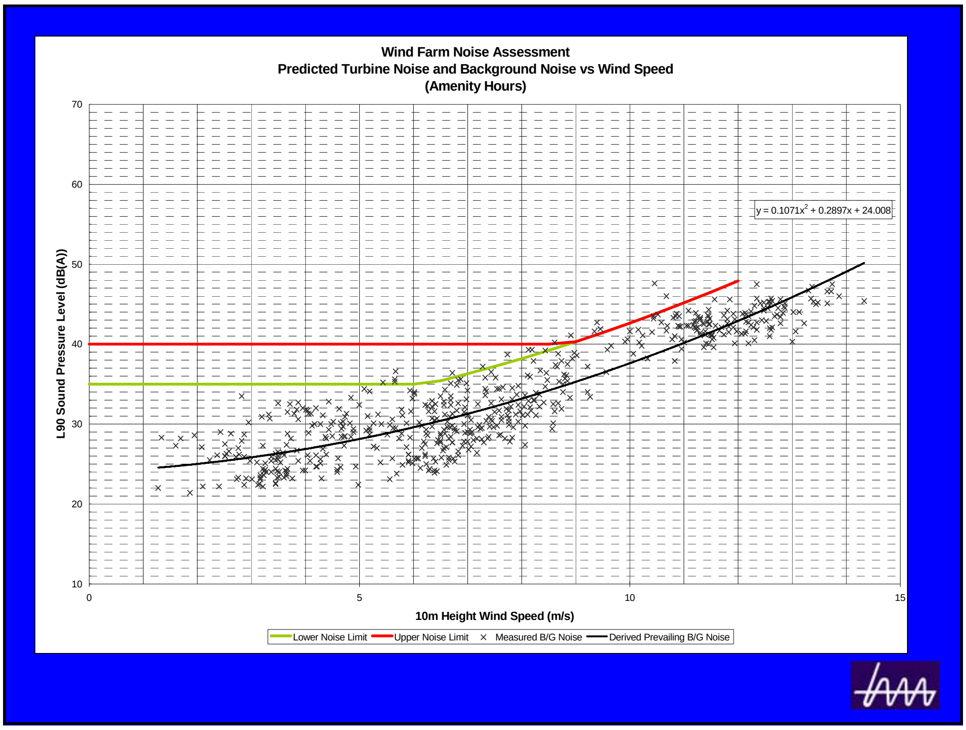

Wind Farm - Baseline Noise Data
20th/21st February 2002
SPL (dB(A))
10m Height Wind Speed (m/s)
Time (Hrs)
12:00:00
15:00:00
18:00:00
21:00:00
0:00:00
3:00:00
6:00:00
9:00:00
12:00:00
Leq
L90
Wind Speed

Derivation of Noise Limits

- For ‘sensitive’ day-time and night time hours:
- For each measurement location:
  - Plot noise against wind speed
  - Derive ‘prevailing’ b/g
  - Derive noise limits




Wind Farm Noise Assessment
Background Noise vs Wind Speed
(Amenity Hours)
L90 Sound Pressure Level (dB(A))
10m Height Wind Speed (m/s)
y = 0.1071x² + 0.2897x + 24.008
Measured B/G Noise
Derived Prevailing B/G Noise


Wind Farm Noise Assessment
Predicted Turbine Noise and Background Noise vs Wind Speed
(Amenity Hours)
L90 Sound Pressure Level (dB(A))
10m Height Wind Speed (m/s)
y = 0.1071x² + 0.2897x + 24.008
Lower Noise Limit
Upper Noise Limit
Measured B/G Noise
Derived Prevailing B/G Noise

Prediction
Recent UK Agreement

Prediction and Assessment of Wind Turbine Noise

Agreement about relevant factors for noise assessment
from wind energy projects

Published in the Institute of Acoustics magazine, Acoustics Bulletin March/April 2009

Prediction

ISO 9613 should be used

Predicted noise level = Source sound power level - Propagation Factors

Prediction

- $L_P = L_W + D - A_{geo} - A_{atm} - A_{gr} - A_{scr} - A_{misc}$

Input =?

20 log d + 11

Downwind – worst case

10 deg C
70% RH

Ground Assumptions, G=?

-2 dB
(more need justification)

Downwind Bending

Input
Source Sound Level

- Measurement standard - IEC 61400-11
- Sound *power* level at integer V_{10} wind speeds
- Ideally cut-in to 12 m/s
- Octave or 1/3 octave band spectra
- Analysis of tonal noise

Prediction
L_W and A_{gr}

- Source Sound Power Level and Ground Assumptions
- Two Options
  1. Warranted Sound Power Level and G = 0.5 (50% hard/soft)
  2. Measured Sound Power Level and G = 0 (hard ground)

Prediction
A_{atm}

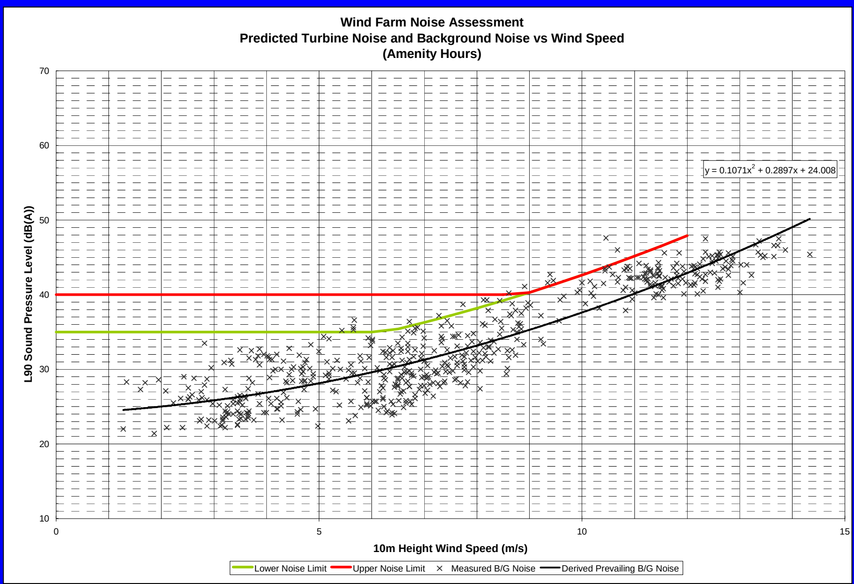
- Atmospheric Absorption
  - 10 degrees C and 70 % humidity
  - Can make quite a significant difference

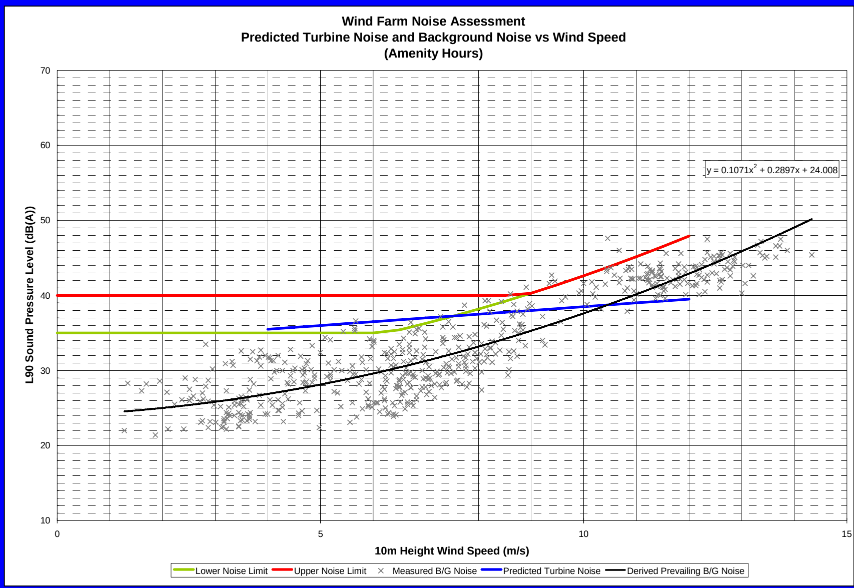
Prediction
A_{scr}

- Screening or Barrier Attenuation
  - Only if no line of sight (topographically) between turbine tip and receiver location
  - 2dB reduction only
  - Greater reduction needs full justification

Impact Assessment

- Comparison of predicted level, over range of wind speeds, with:
  - ETSU-R-97 noise limits
  - Baseline
- For worst case wind direction

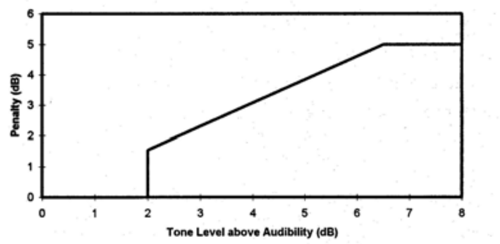




Other Issues

- Tonality
- Amplitude Modulation
- Infrasound (<20 Hz)
- Low Frequency (20Hz – 200Hz)
- Wind Shear (variation of wind speed with height)

ETSU-R-97 Tone Penalty



Penalties for tonal noise

Modulation

- ETSU-R-97 noise limits allow for the fact that there may be a degree of fluctuation at times.
- Occurs at turbines but diminishes with distance.
- Taller turbines – greater modulation
- Factors leading to excess modulation not known
- More of a problem indoors?

Modulation

- Planning Inspectors worried about excess amplitude modulation
- Controllable through Planning Conditions?
- How predictable is it?
- How much of an issue is it?

Conclusions

- Assessment/Limits
  - Reliance on accurate measurements of background noise level
- Predictions – should they be based on:
  - Worst Case
  - Typical Worst Case
  - Average
- Complaints procedure and compliance measurements and assessment time consuming
  - Wind farms have been refused on this basis

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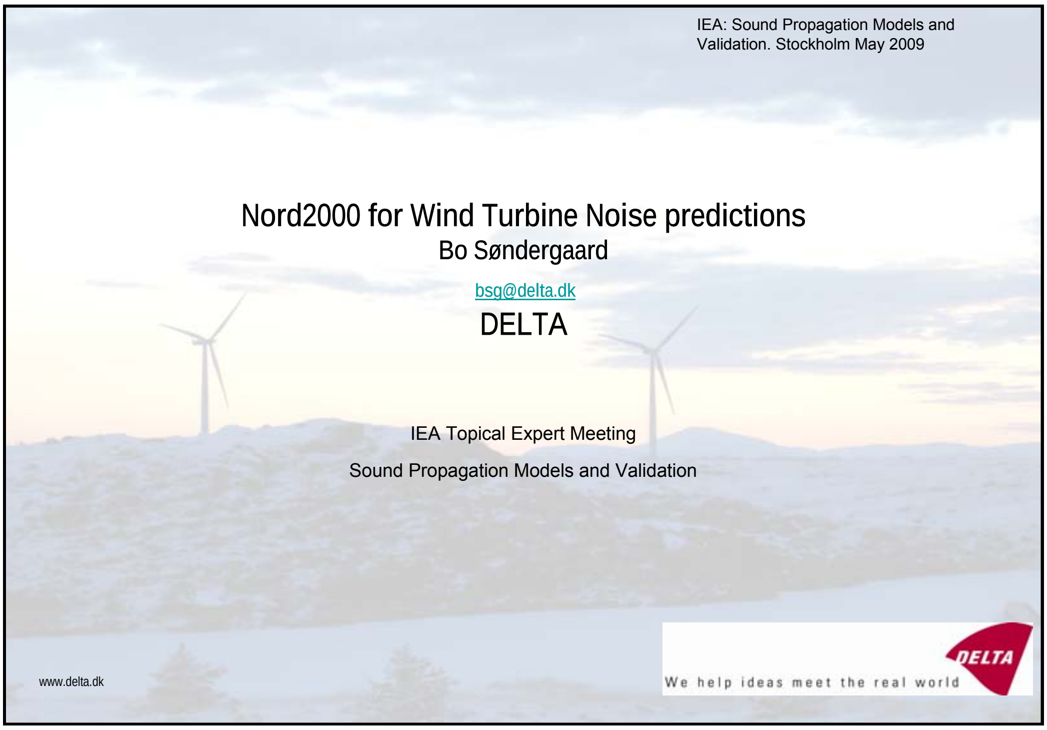

Nord2000 for Wind Turbine Noise predictions

Bo Søndergaard

bsg@delta.dk

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IEA Topical Expert Meeting

Sound Propagation Models and Validation

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Motivation for improved predictions

- Increasing number of wind turbines
- Larger wind farms
- ↓
- More people are exposed to noise from wind turbines
- Larger consequence areas around the wind farms
- ↓
- Demand for better prediction tools
  - Propagation models
  - Noise descriptors
  - Software implementations

Prediction Method

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- Ground effect

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Prediction Method

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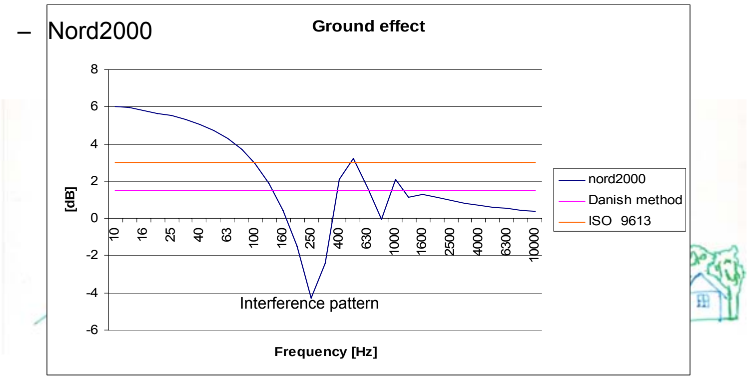
- Ground effect
  - Nord2000



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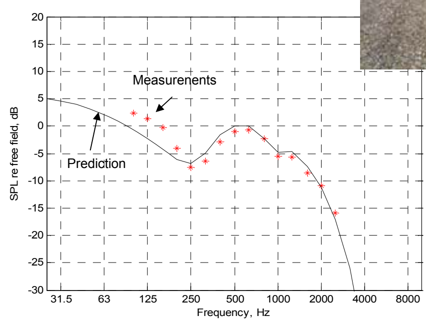
Prediction Method

- Ground effect
  - Nord2000



Down wind propagation – distance 1500 m

Meteorological input parameters in Nord2000

z_0	Roughness length (m)
A	Coefficient of the logarithmic part of the sound speed profile
B	Coefficient of the linear part of the sound speed profile
s_A	Standard deviation of A from short-term meteorological fluctuations
s_B	Standard deviation of B from short-term meteorological fluctuations
t_0	Temperature at the ground (°C)
C_v^2	Structure parameter of turbulent wind speed fluctuations ($m^{4/3}s^{-2}$)
C_T^2	Structure parameter of turbulent temperature fluctuations (Ks^{-2})
t_{air}	Mean temperature along propagation path, used for air absorption (°C)
RH	Mean relative humidity along propagation path, used for air absorption (%)

Log-lin sound speed profile

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

Effective sound speed, moving atmosphere

$$c_{eff}(z) = u(z) + c(T(z))$$

u(z) = component of wind at height z perpendicular to wave front

c(T(z)) = sound speed at temperature T at height z

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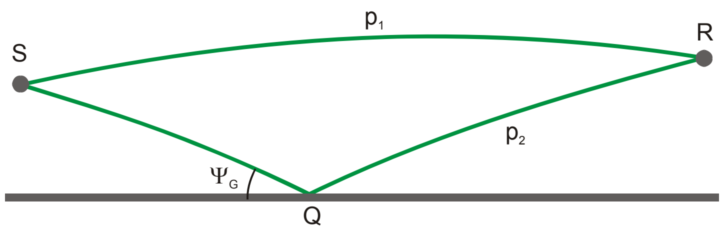
Flat terrain, curved rays, downward refraction



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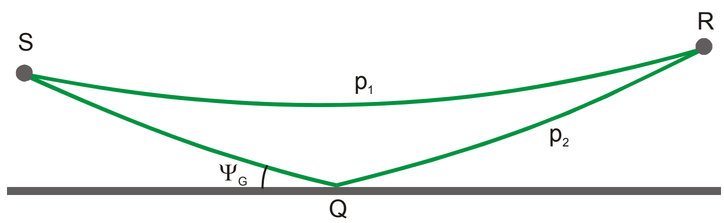
Flat terrain, curved rays, upward refraction



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Validation of Nord2000

- Validation through Loudspeaker measurements
- Validation through single Wind Turbine measurements
- Validation through Wind farm measurements

With emphasis on the loudspeaker measurements

Simultaneous

- registration of noise at the source and at several distances
- registration of meteorological parameters for noise prediction

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Measurement site at Høvsøre

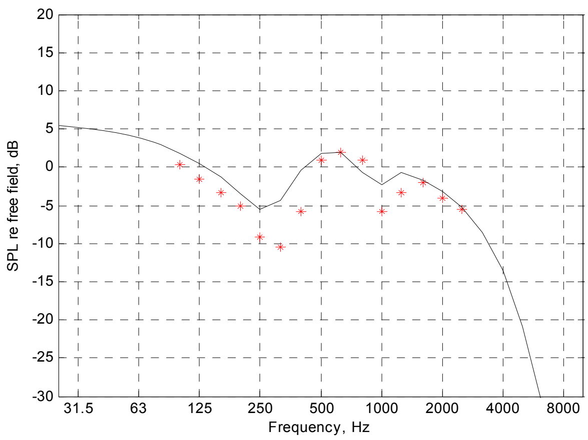
The loudspeaker position was changed to get results from up- and downwind

In the figure medvind is downwind and modvind is upwind

Groups for averaging propagation effect

- Downwind or upwind
- Source height 30 or 50 m
- Receiver height 2 or 5 m
- Distance 500, 1000 or 1500 m

Average: downwind, source 30 m, receiver 2 m, distance 500 m



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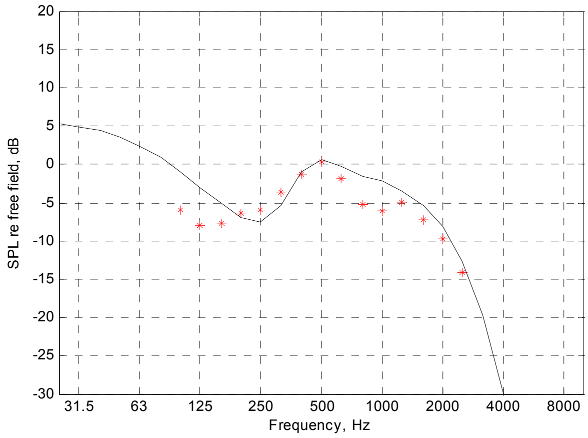

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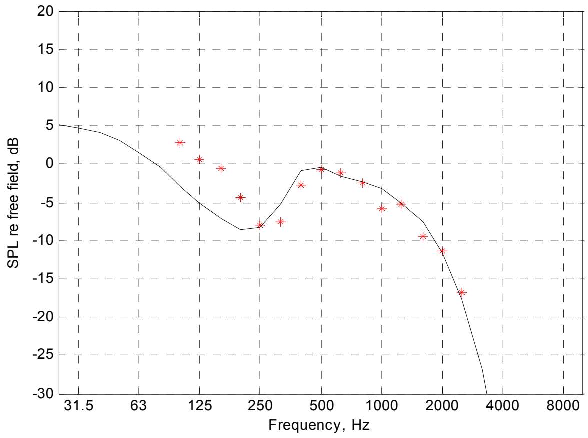
Average: downwind, source 30 m, receiver 2 m, distance 1500 m



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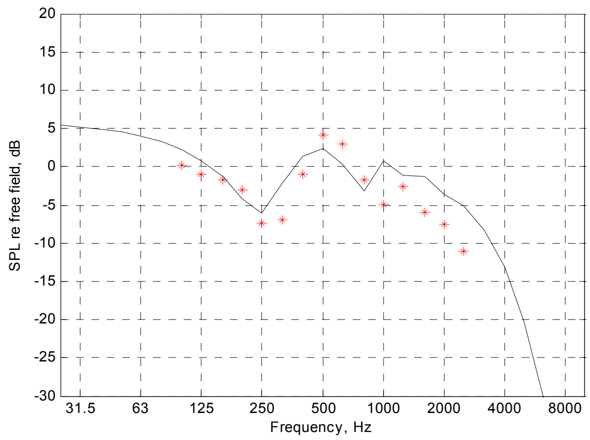
Average: downwind, source 50 m, receiver 2 m, distance 500 m



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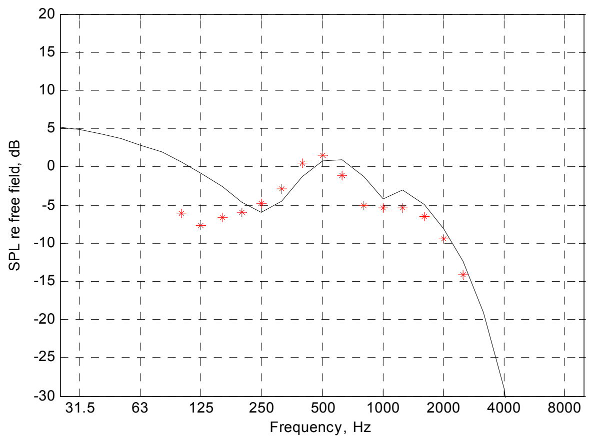

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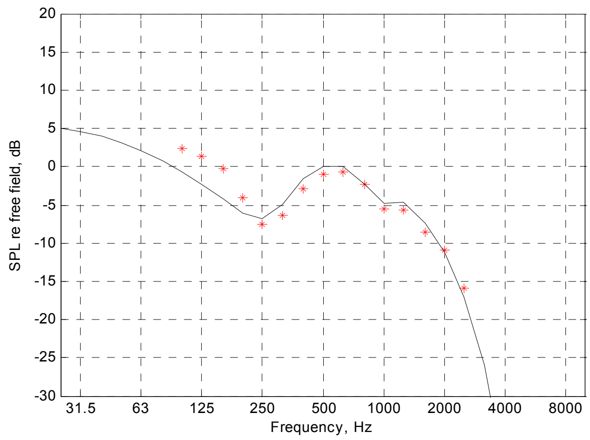

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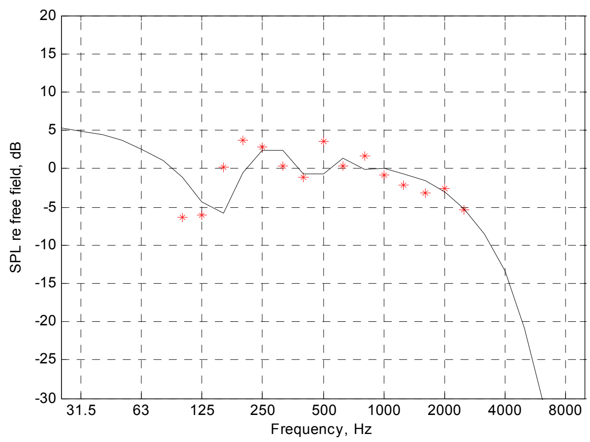

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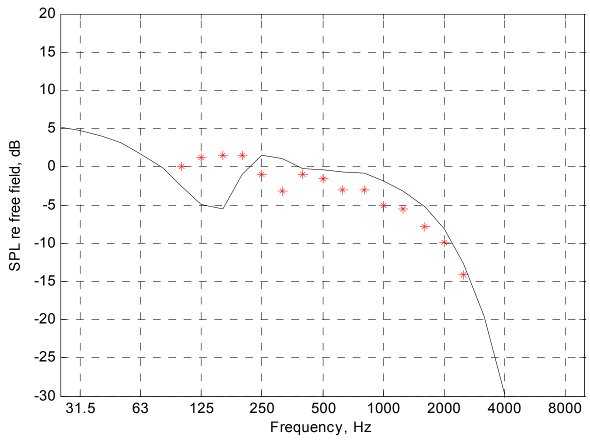

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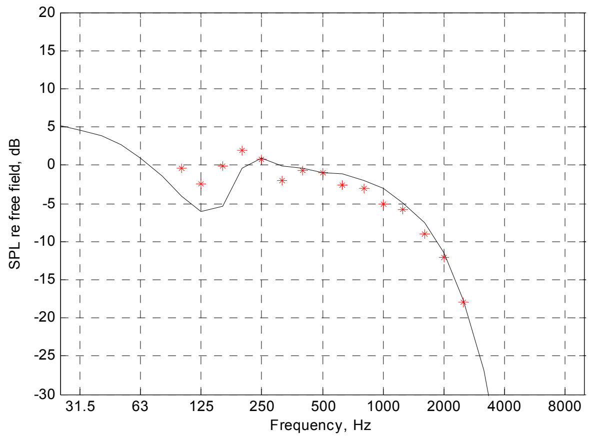

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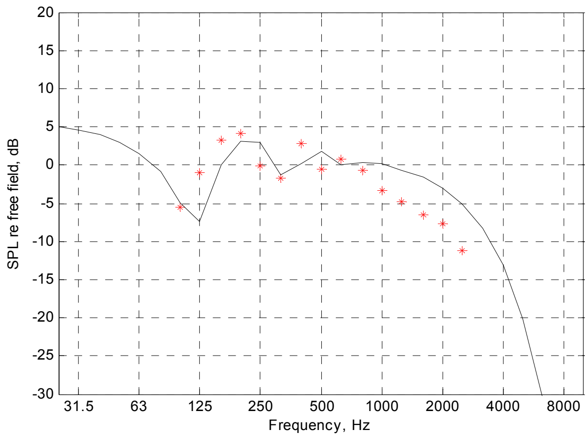

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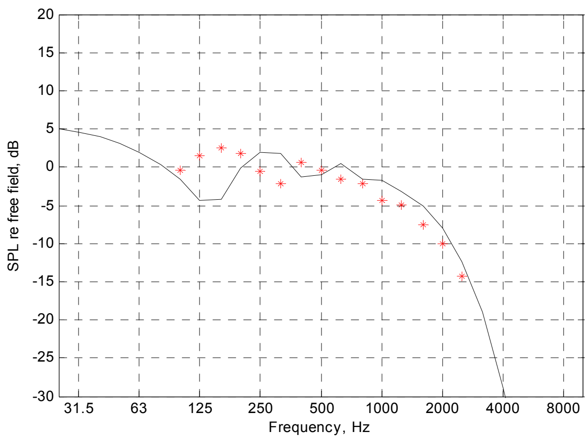

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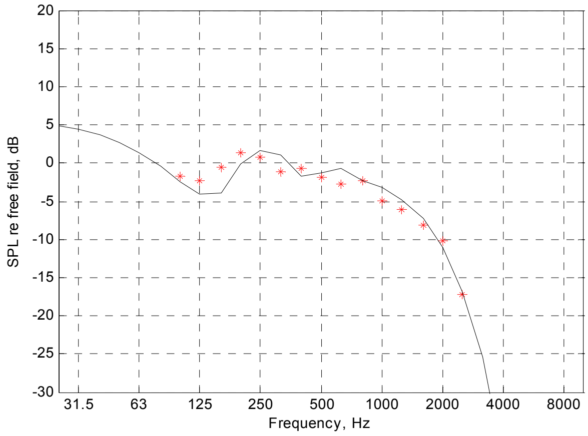

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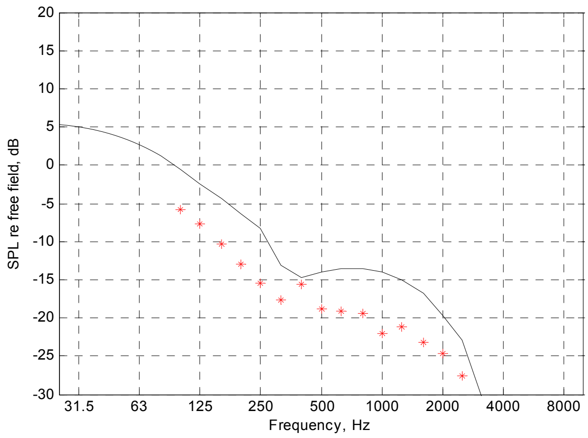
Average: upwind, source 30 m, receiver 2 m, distance 1000 m



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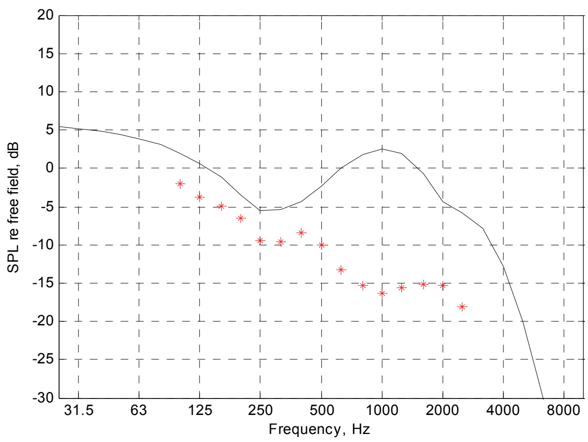
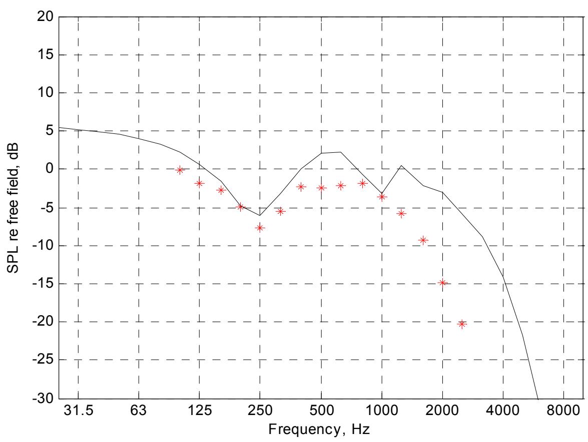
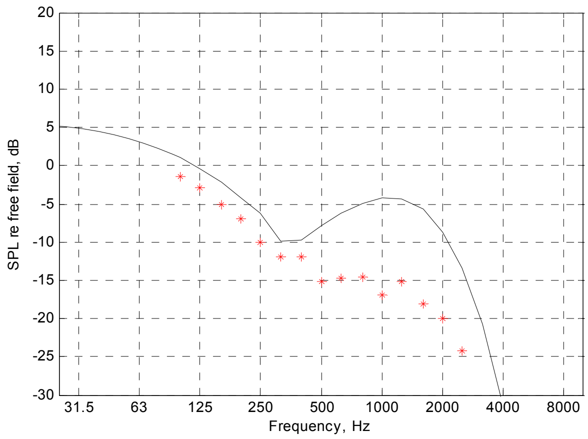


Average: upwind, source 50 m, receiver 2 m, distance 500 m



Average: upwind, source 50 m, receiver 2 m, distance 1000 m



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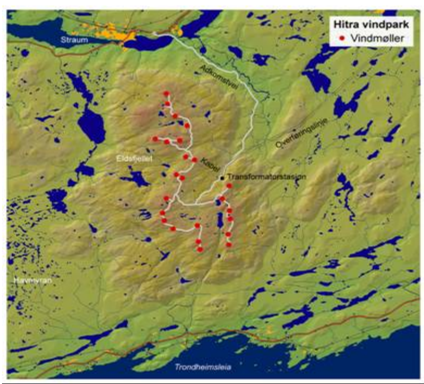
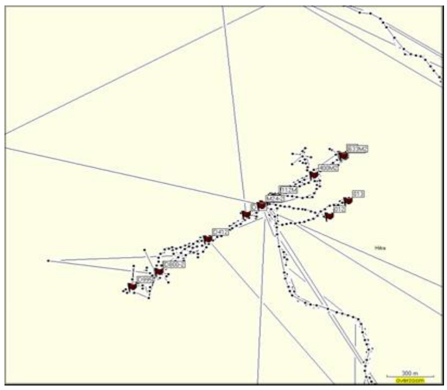
Measurement site at Hitra





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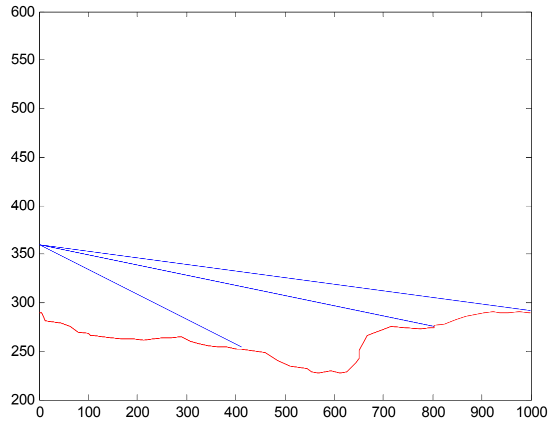
Downwind, pos. 1, 2, and 3



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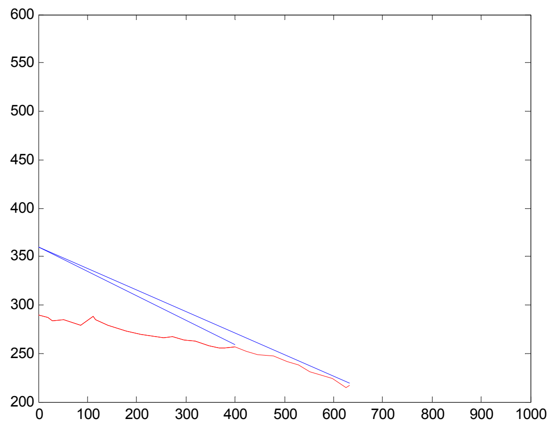
Upwind, pos. 1 and 2



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Downwind, pos. 1

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Downwind, pos. 2

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Downwind, pos. 3

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Loudspeaker position

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Measurements at Hitra

- Loudspeaker measurements
- Wind turbine measurements

- Results similar to Høvsøre measurements
- Results with negativ wind shear was predicted well

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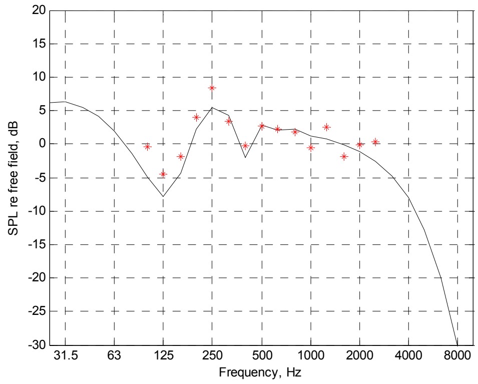
Downwind, pos. 1, h_R = 2 m, 400 m



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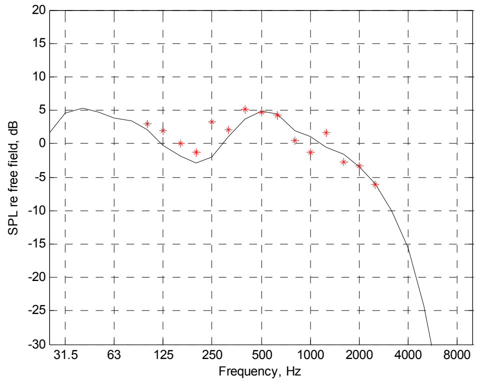
Downwind, pos. 2, h_R = 2 m, 800 m



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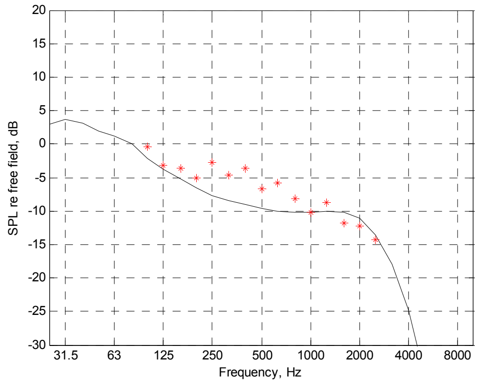
Downwind (8-7), pos. 3, h_R = 2 m, 1000 m

Typical shadow zone behaviour in downwind direction due to negative wind shear.

Notice reasonable agreement between measurements and prediction



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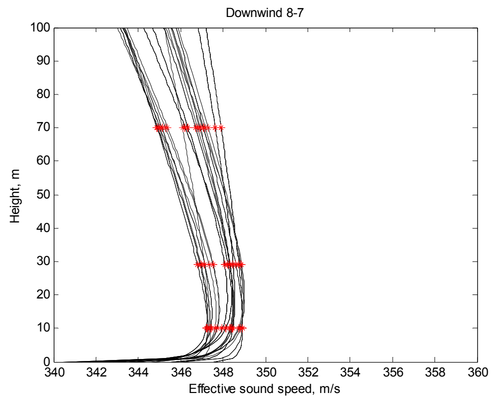
Sound speed profile, downwind (8-7)



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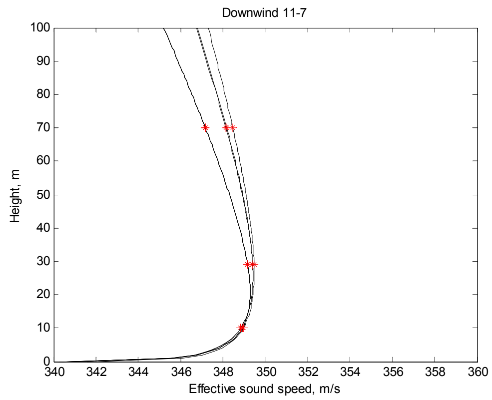
Sound speed profile, downwind (11-7)



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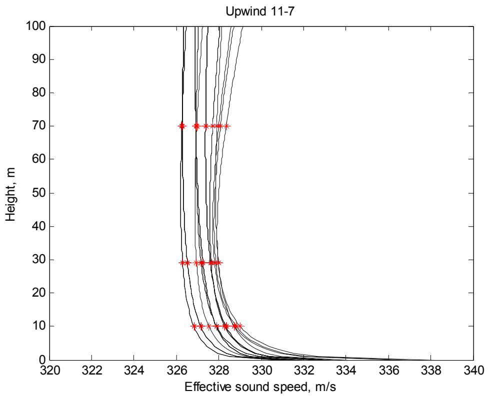
Sound speed profile, upwind (11-7)



Conclusions

- Good agreement between measured and predicted values of ground effect
- Apparent overestimation of the noise in the shadow zone
- Difficulties in prediction the exact occurence of the shadow zone
- Good results with negative shear
- With detailed meteorological information it is possible to calculate annual averages (LAeq, Lden) Statistical distributions of the noise, Maximum levels, …..

Conclusions continued

- More precise (meteorology dependent) prediction models makes noise measurements around wind farms more relevant.
- There is need for more precise noise immission measurement methods including recommendations for which meteorological conditions to measure and how to do it.
- Long term noise measurements can be replaced by short term measurements supplied by predictions.

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Long range sound propagation over a sea surface

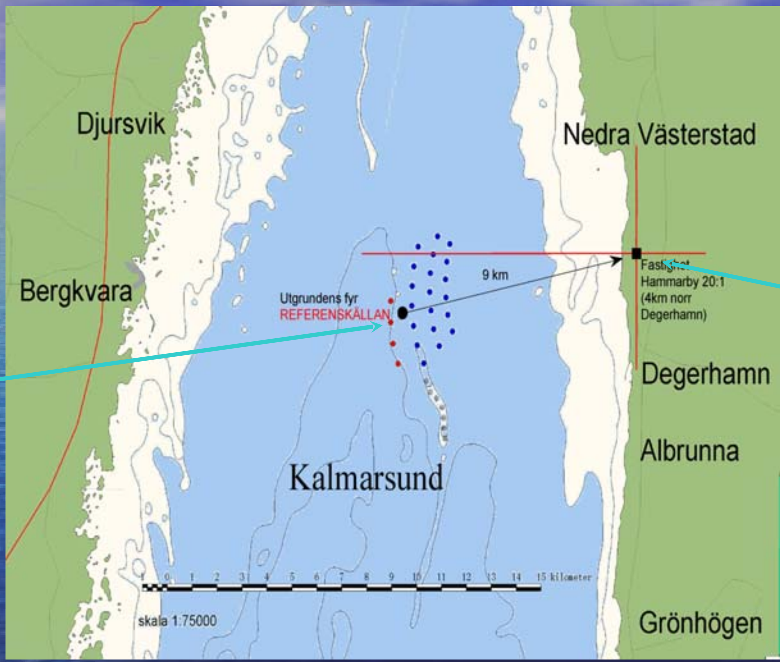
Karl Bolin and Ilkka Karasalo

Measurements and model predictions of sound propagation in the Kalmar strait

Outline

- Experimental data
  - Meteorological data
  - Acoustical data
- GFPE-model
  - Description
  - Parameter selection
- Results
  - Modelled soundfield
    - Downwind => sound channel, cylindrical TL
    - Upwind => upward refraction, sound shadow at ground
    - Turbulence => random scattering, shadow less pronounced
  - Measured and modelled TL, laminar atmosphere
  - Measured and modelled TL, turbulent atmosphere

Experimental site



Utgrunden lighthouse two sources

Hammarby Receiver array

Sound sources - siren and loudspeaker

Utgrunden

Receiver–array of 8 microphones

HAMMARBY (ÖLAND)

Available data from 15-21/6 2005

(Vindforsk project TRANS, KTH and UU)

Sound transmission loss data

80 Hz (98 registr)

200Hz (174 registr)

400 Hz (174 registr)

Meteorological data

u, v: 59 profiles up to height 3-4.5 km from teodolite tracking of balloons

T, p, h: 19 profiles up to height 6.5-13 km from Vaisala RS80 radiosounder

Greens Function Parabolic Equation

$$\phi = exp(-ik_0 r)pr^{1/2}$$

$$\begin{aligned}\phi(r+\Delta r, z) = \exp\left(i\frac{\Delta r \delta k^2(z)}{2k_r}\right) \\ \times\left[\frac{1}{2\pi}\int_{-\infty}^{\infty}(\Phi(r,k') + R(k')\Phi(r,-k'))\right. \\ \times\, exp(i\Delta r(\sqrt{k_r^2 - k'^2} - k_r))e^{ik'z}dk' \\ +\, 2i\beta\Phi(r,\beta) \\ \left.\times exp(i\Delta r(\sqrt{k_r^2 - \beta^2} - k_r))e^{-i\beta z}\right]\end{aligned}$$

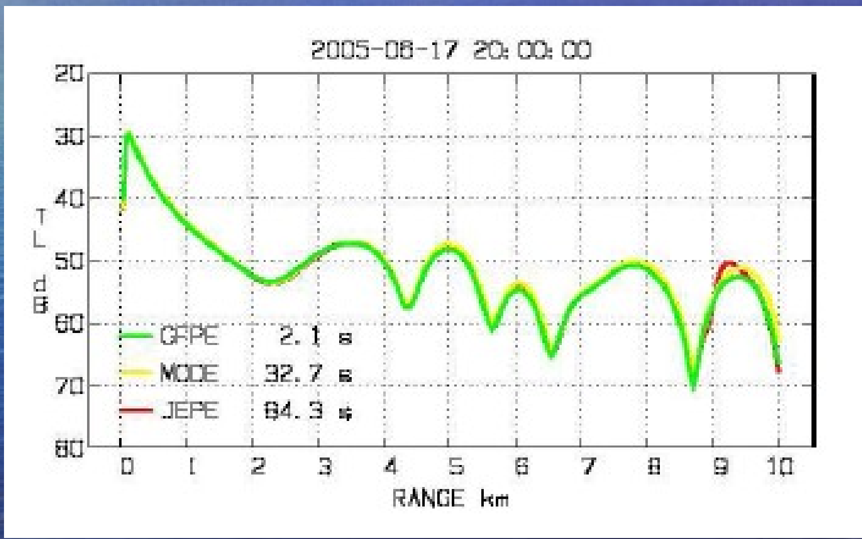
$$\Phi(r,k) = \int_0^{\infty} exp(-ikz')\phi(r,z')dz'$$

- K. E. Gilbert and X. Di, A fast green's function method for one-way sound propagation in the atmosphere", Journal of the Acoustical Society of America 94, 2343-2352 (1993).
- E. M. Salomons, Improved greens function parabolic equation method for atmospheric sound propagation", Journal of the Acoustical Society of America 104, 100-111 (1998).

GFPE model ingredients

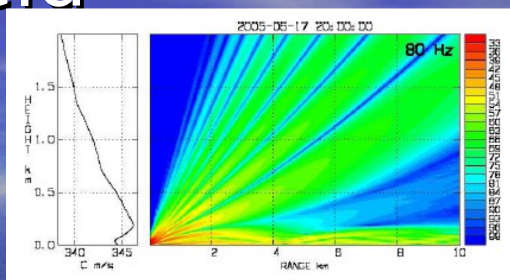
- Gaussian source profile
- Vertical region 0<= z <= 2000 m
- Artificial absorption layer at upper boundary
- Attenuation (freq, temp, humidity, pressure)
- Ground impedance (Delaney Basley)
- Turbulence (hom random fields, von Karman)

GFPE validation
Geometry of experimental site
Atmosphere of June 16, 20:00

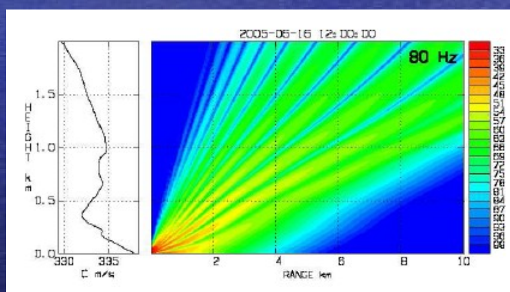


Predicted soundfield

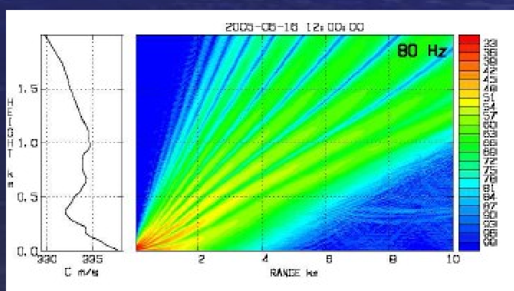
- Downwind conditions



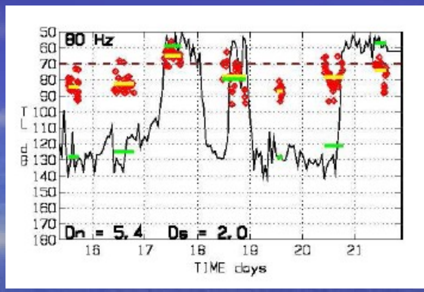
- Upwind conditions, laminar windfield

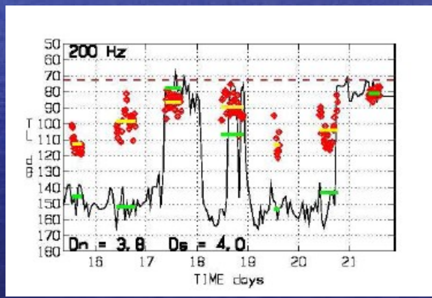


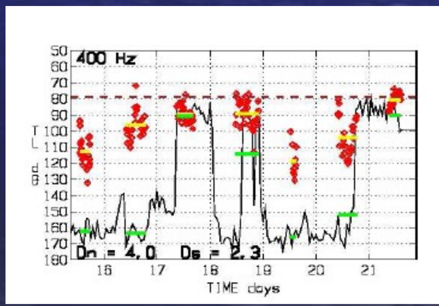
- Upwind conditions, turbulent windfield



Transmission loss
Laminar windfield

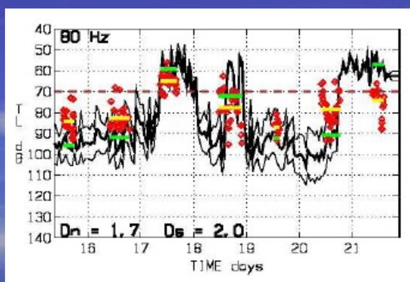


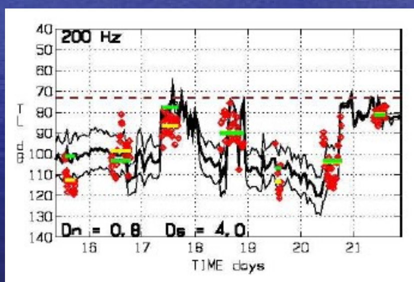


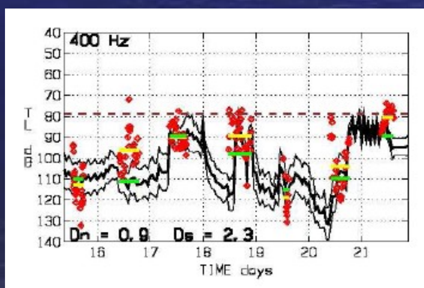


- Predicted TL too large at upwind conditions – refractive sound shadow
- Good agreement at downwind conditions

Transmission loss
Turbulent windfield







- Predicted TL at upwind conditons significantly improved

Conclusions

- Meteorological variations important
- Predicted TL follows experimentally observed variations in a realistic way
- Sound propagation model should include effects of turbulence

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TOPICAL EXPERT MEETING ON
SOUND PROPAGATION MODELS AND
VALIDATION

Denis Siponen
VTT Technical Research Centre of Finland

Current sound propagation models used in windfarm design

Usually based on Emispherical spreading[1]

$$L_P(R) = L_W - 10\log_{10}(2\pi R^2) - \Delta L_a$$

In case of several turbines

$$L_{1+2+..} = 10\log_{10}(10^{L_1/10} + 10^{L_2/10} + \ldots)$$

Limitations:

- -No topography
- -No vegetation
- -No reflections
- -No weather conditions

1: Wiley: Wind energy handbook, eq 9.14

2

Some possibilities for calculating noise immission in the vicinity of wind farms

CadnaA

CadnaA is a program for noise and air pollution prediction and efficent for expert purposes.

Program calculates (ray tracing) and predicts noise immission L_{den} only according to national and international standards and regulations.

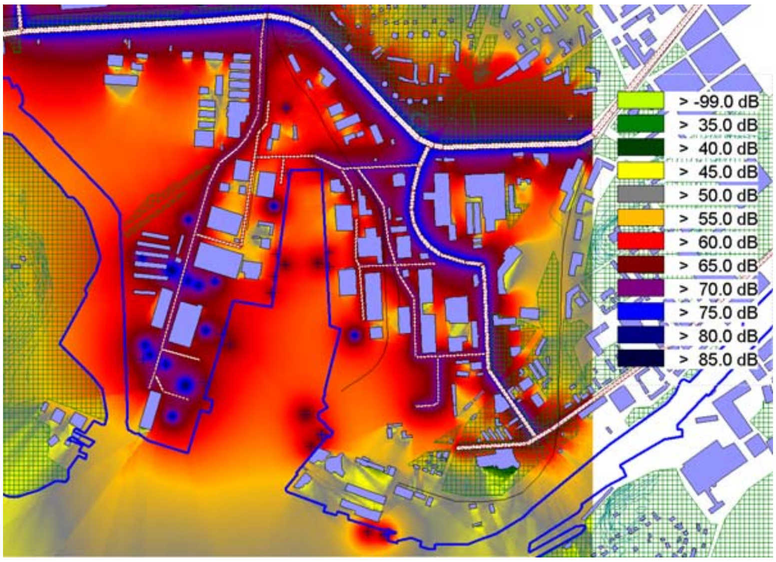
Pros

- Source:
  - Wind turbine could be modeled as point source (coordinates, height, directivity, noise spectrum in octave bands, operation time
- Evinroment:
  - Topography
  - Obstacles (buildings, etc)
  - Vegetation (areas with various ground absorption)
  - Basic modeling of weather conditions

Cons

- Inversion is not accounted in weather conditions modeling

VTT TECHNICAL RESEARCH CENTRE OF FINLAND



5

VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Atmosaku

- Program is for accurate prediction of sound propagating in different weather conditions. Developed by VTT.
- A hybrid model, based on a state-of-the-art physical model, uncertainties by a statistical model.
    - Physical model is based on narrow angle CNPE (Crank-Nicholson Parabolic Equation) and GTPE (Generalized Terrain parabolic equation) methods
    - Statistical model is based on measurement data of 612 days

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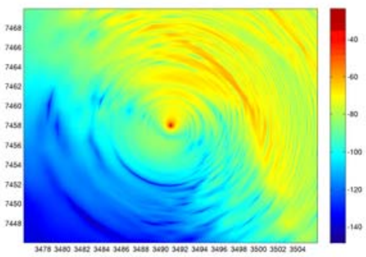
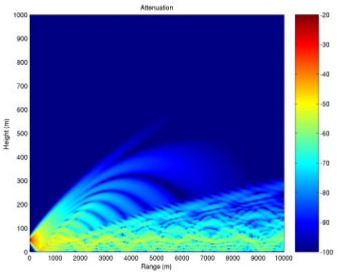
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Example:

400 km2 area (left), topography from a specific area in Finland, frequency 50 Hz, GTPE method, Weather conditions: inversion,wind SW.





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VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Pros

- Source:
  - Wind turbine could be modeled as point source (coordinates, height, directivity, noise spectrum
  - Gives uncertainties of the calculations at different weather conditions: Attenuation X dB ± Y dB
- Evinronment:
  - Topography
  - Obstacles (buildings, etc)
  - GTPE model takes account for topography and ground impedance
  - Extremely detailed weather conditions modeling

Cons

- All features not included yet, still in development
- (Obstacles like buildings needs to be approximated due to limitations of GTPE method)

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VTT creates business from technology
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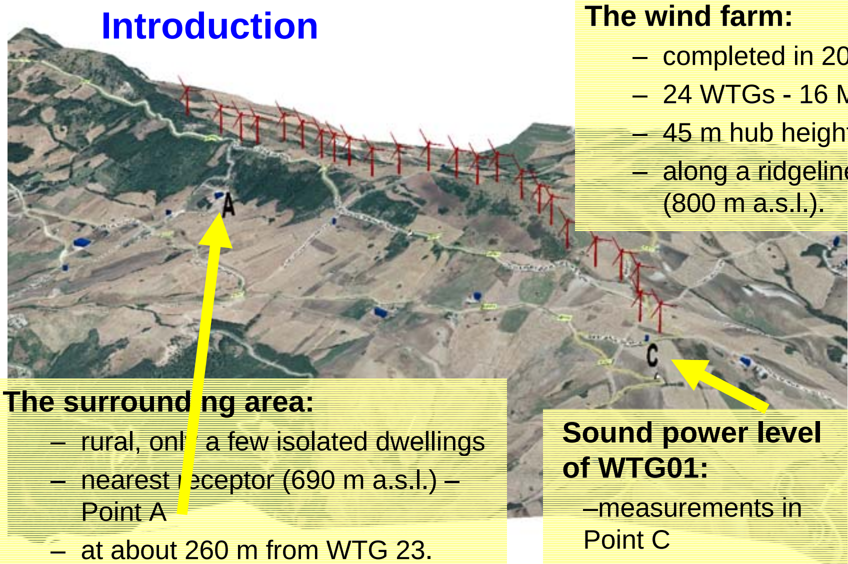
Environment and Territory Division of CESI S.p.A.

Wind farm noise measurements and residual noise estimation by modeling

Roberto Ziliani

Introduction



The wind farm:

- completed in 2005
- 24 WTGs - 16 MW
- 45 m hub height
- along a ridgeline (800 m a.s.l.).

The surrounding area:

- rural, only a few isolated dwellings
- nearest receptor (690 m a.s.l.) – Point A
- at about 260 m from WTG 23.

Sound power level of WTG01:

–measurements in Point C

Introduction

- **Aims of the study:**
  - characterizing the environmental noise of the site;
  - getting an estimation of the residual noise level of the site, without turning off the wind farm;
  - checking the compliance of the plant with Italian noise regulation.

Noise regulation in Italy (1)

- **Limits**
  - Max. absolute immission limit → ambient noise
    Outside buildings
  - Differential immission limit (specific source)
    → ambient noise – residual noise
    Inside buildings
  - Emission limit → noise contribution of a specific source.
    Outside buildings
- **No special regulation for wind farms noise measurement or assessment**

Noise regulation in Italy (2)

- **Reference periods**
  - daytime (h. 6.00 ÷ 22.00)
  - nighttime (h 22.00 ÷ 6.00).
- **Zoning plan**
  - Six kinds of classes are defined
    - class 1: Protected areas → class 6: Industrial areas
  - Immission/Emission limits are established for each class and for daytime/nighttime reference periods
  - Each portion of territory must be assigned to a class
    - Zoning not yet approved → general transitory limits

Presentation *Wind farm noise measurement and residual noise estimation by modeling*

Phases of the study (1)

1. **Experimental surveys:**
   - automatic long term environmental noise measurements at the receptor location (point A)
   - calculation of sound power level of WTG01, according to the standard IEC 61400-11 by means of measurement in point C.

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Phases of the study (2)

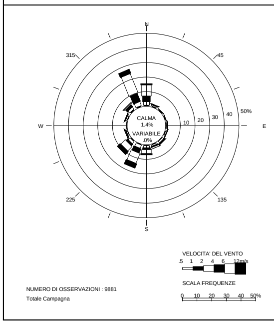
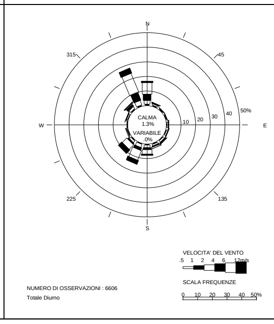
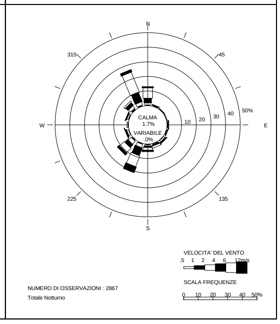
2. Data processing:

– Mathematical modeling of the wind farm noise contribution at the receptor location – Point A;
– Joint analysis of sound levels, windspeed and electrical power output data, in order to:
  - estimate the residual noise level,
    – as difference between the measured ambient noise level with WTGs on and the noise level contribution of WTGs, obtained by mathematical modeling;
  - verify the results obtained vs. existing national environmental noise limits.

1. Experimental surveys

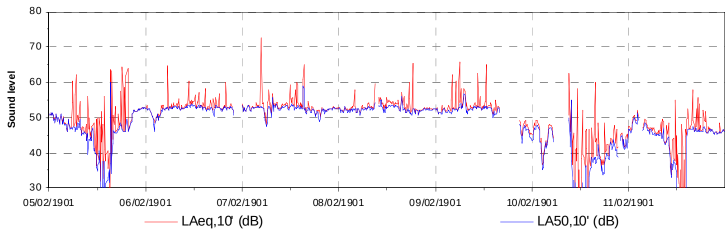
- **Automatic long term measurements - Point A**
  – Total measurement period → Three months
  – Acquisition of:
    - L_{Aeq}, L_{AN}, 1/3 octave band spectra (L_{eq}, L_N)
    - Electrical power output of each WTG
    - Wind speed and wind direction at the 10 m height wind farm anemometer
    - Wind speed and rain in the vicinity of microphone position
  – Measurement time: 10’

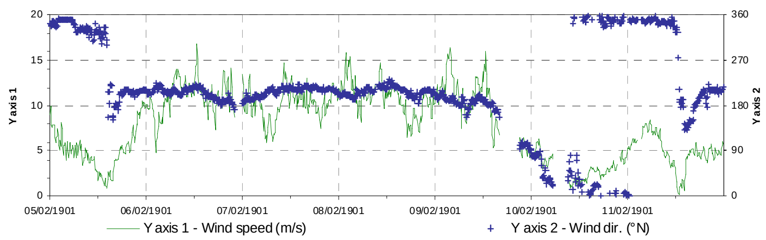
Wind conditions during the noise survey

Total	Daytime reference period	Nighttime reference period
		

- Prevailing directions: → NNW, SSW, N and SW, respectively with about 30%, 20%, 15% and 12% of occurrence.
- WTGs operated for about 60-65 % of the total measuring time, with an average electrical power of about 310 kW each.

Point A - Noise and wind - Time history





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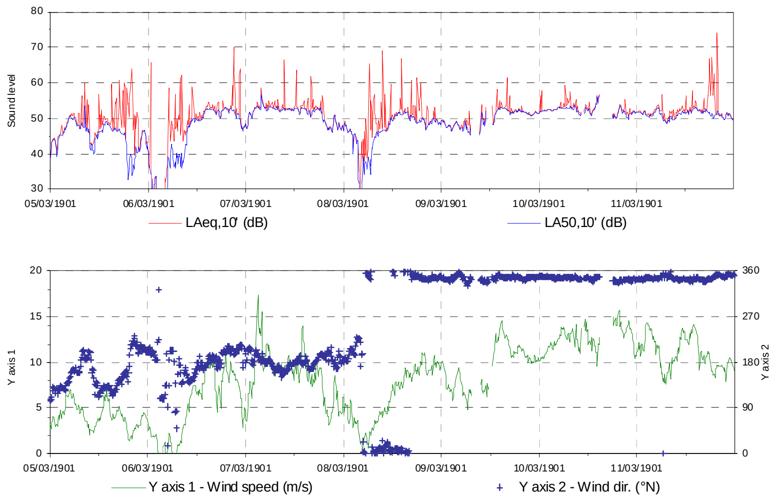
Presentation ***Wind farm noise measurement and residual noise estimation by modeling***

Point A - Noise and wind - Time history



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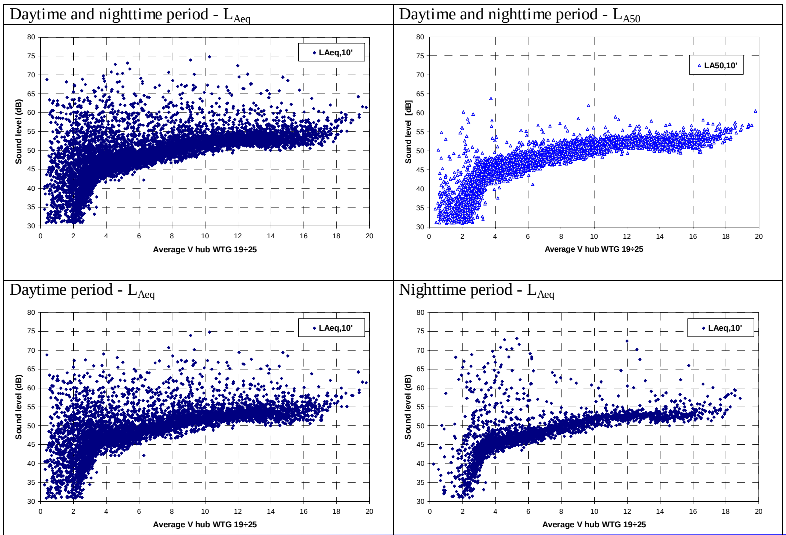
Presentation ***Wind farm noise measurement and residual noise estimation by modeling***

Point A - Noise vs. wind speed



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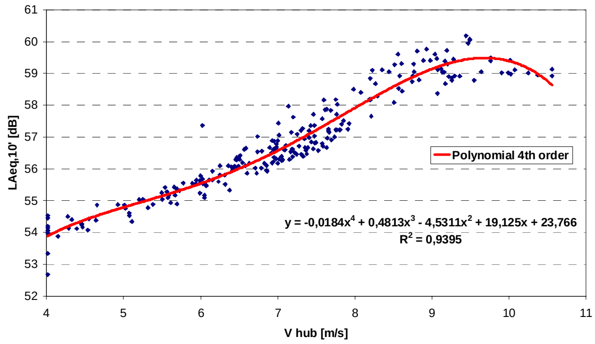
1. Experimental surveys

- **WTG01 sound power calculation**
  - according to IEC 61400-11;
  - total measurement period: 7 hours
  - measurement time 1’
  - L_{Aeq}, L_{AN} and 1/3 octave band spectra;
  - WTG 01 electric power output acquisition;
  - aim of the activity: calculation of $L_{WA} = f(P_{el})$.

L_{WA} calculation - Data analysis (1)

- **$L_{Aeq,1'}$ vs. V_{hub}**
  - 4th order polynomial.



L_{WA} calculation - Data analysis (2)

- **for V_{hub} corresponding to V_S=4, 5, 6, 7 m/s**
  - calculation of L_{Aeq}
    - using the regression curve of the 4th order formerly obtained
  - calculation of L_{WA}
    - by

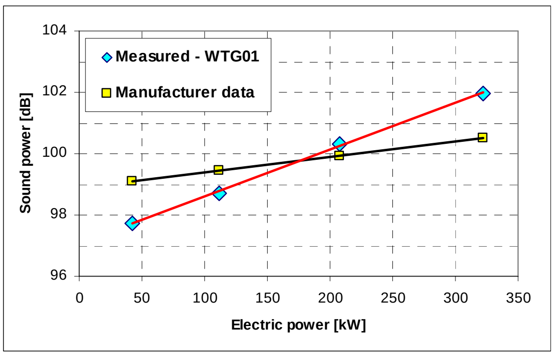
$$L_{WA,k} = L_{Aeq,c,k} - 6 + 10\log\left[\frac{4\pi R_1^2}{S_0}\right]$$

  - calculation of the electric power (P_{el})

Presentation *Wind farm noise measurement and residual noise estimation by modeling*

L_{WA} calculation - Data analysis (3)

- **Calculation of the regression line between L_{WA} and P_{el}:**
  - $L_{WA} = 0.0151 \cdot P_{el} + 97.095$



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Presentation *Wind farm noise measurement and residual noise estimation by modeling*

2. Data processing

- **Step 1: mathematical modeling**
  - estimate the noise contribution of WTGs at receptor location (point A), starting from P_{el} gathered during the survey $L_{WTG} = f(P_{el})$
- **Step 2: Residual noise calculation**
- **Step 3: Immission level calculation**
  - with all the WTGs operating.

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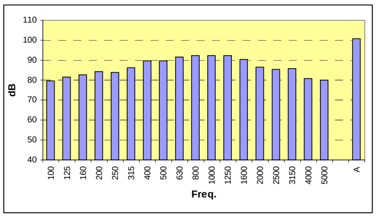
Presentation *Wind farm noise measurement and residual noise estimation by modeling*

Step 1 - Mathematical modeling (1)

- N° 24 point sources at hub height;
- three-dimensional terrain model;
- receptor area: reflective ground (G=0.9); surrounding area: absorbent ground (G=0.1);
- SoundPlan, ISO 9613-2 propagation standard;
- spectrum from manufacturer's data.



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Presentation *Wind farm noise measurement and residual noise estimation by modeling*

Step 1 - Mathematical modeling (2)

- **General propagation formula:**

$$L_p = L_W - \sum_i A_i$$

Cumulative effect of attenuation terms:
A_{div} (geometrical divergence),
A_{gr} (ground effect),
A_{screen} (screening),
A_{atm} (atmospheric abs.),
A_{misc} (miscellaneous effects).

The cumulative effect of attenuation terms between each WTG and point A was obtained by running SoundPlan and calculating the difference L_W - L_p.

WTG	$\sum_i A$ dB(A)
WTG 19	66.1
WTG 20	62.3
WTG 21	62.6
WTG 22	61.4
WTG 23	59.8
WTG 24	61.3
WTG 25	63.5

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Presentation *Wind farm noise measurement and residual noise estimation by modeling*

Step 1 - Mathematical modeling (3)

- **Calculation of WTGs noise contribution at point A**

$$L_{WTG} = L_{WA} - \sum_i A_i$$

→ **Spreadsheet**

Sound level contribution of WTGs at the receptor (point A); is the log-sum of each WTG contribution.

Sound power level of WTG, it is calculated from electric power output of each WTG, collected on 10' basis during long term monitoring in point A

Calculated

For each 10' measurement interval, noise level contribution of wind farm was calculated.

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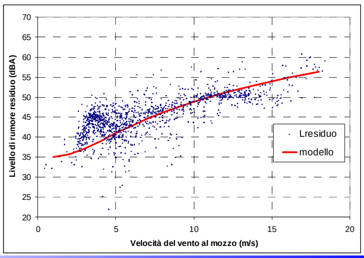
Step 2: Residual noise calculation

- **Ambient noise - L_{WTG} = Residual noise**
  - calculation performed by the model;
  - 10' measurement periods with L_{Aeq}-L_{A50}> 5 dB were excluded from calculus;
  - a regression curve was estimated f(V_{hub})

$$L_{res} = 10 \cdot \log_{10} \cdot \left(\left(10^{0.1 \cdot L_{base}} \right) + 73 \cdot V_{hub}^{esp} \right)$$



- L_{base} residual noise with no wind (35 dB(A))
- V_{hub} [m/s]
- esp = 3, wind energy ∝ V^3

Presentation *Wind farm noise measurement and residual noise estimation by modeling*

Step 3 - Immission level calculation

- **Absolute noise immission level:**
  - L_{amb} = L_{res} + L_{WTG} (log sum)
    - with all WTGs operating

- **Differential immission level:**
  - L_{diff} = L_{amb} - L_{res} (arithmetical subtraction)
  - L_{diff} is an estimate, outside buildings, of the inner value.

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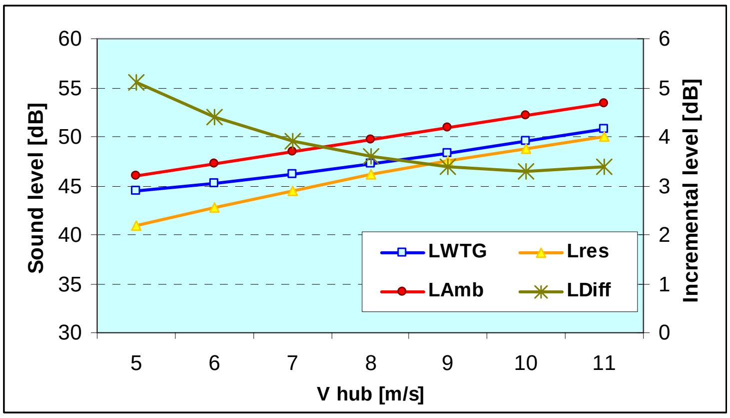
Step 3 - Immission level calculation - Results



Sound emission and sound propagation in forest terrain IEA 5-6 May 2009

1

Nytänkande med erfarenhet

Content

- Wind turbines in forest terrain
- Sound emission measurements
- Sound immission measurement
- Noise compliance check

2

Nytänkande med erfarenhet

Wind research project

- V-201 *Ljudspridning kring havsbaserade vindkraftverk. Projektledare Mats Åbom, Marcus Wallenberglaboratoriet, KTH*
- V228 *Maskering av ljud via vindinducerat bakgrundsbuller. Projektledare Mats Åbom, Marcus Wallenberglaboratoriet, KTH*
- V-233 *Prediktering av vindkraftbuller baserad på detaljerad meteorologisk och geografisk information. Projektledare Ilkka Karasalo, avdelning Människa och teknik, FOI*
- V-164 Sound emission and sound propagation for wind turbines in forest terrain *Project leader Martin Almgren, ÅF-Ingemansson*

3

Nytänkande med erfarenhet

Martin Almgren

- M.Sc Engineering Physics, Chalmers University of Technology 1977
- Fläktfabriken, Götaverken 1977-1981
- Ph.D. Applied Acoustics, Chalmers University of Technology, Acoustic scale modelleing of outdoor sound propagation 1986
- 3K Akustikbyrån, SSPA, KM, J&W 1986-2002
- Ingemansson Technology, now ÅF-Ingemansson since 2002

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Nytänkande med erfarenhet

ÅF-Ingemansson

- Ingemansson was founded 1956
- Ingemansson Technology AB was bought by ÅF 2006
- More than 100 consultants specialised in sound and vibration
- Located in 12 cities in Sweden, Norway and Denmark

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Nytänkande med erfarenhet

Facts at a glance

Co-workers	4 500
Offices in	more than 100 locations
Represented in	some 20 countries
Sales (pro forma)	€ 400 million

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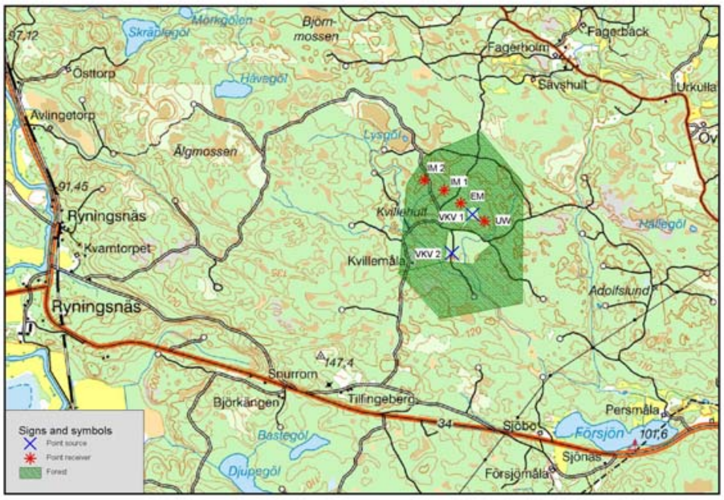
Nytänkande med erfarenhet

Wind turbines in forest terrain



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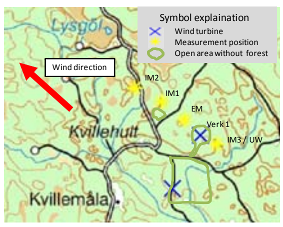
Wind turbines in forest terrain

- A wind turbine in a forest terrain does not emit higher sound power than a wind turbine in flat farming terrain at the same wind speed
- Sound immission inside the forest is slightly higher than predicted with Nord2000
- The tree stems causes sound scattering and reverberation
- Apparent point source is OK
- Sound absorption shall be taken into account in IEC 61400-11



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Sound emission measurements

- The standard for determination of sound power level for wind turbines should be revised
- Atmospheric sound absorption should be added
- The sound power level should be stated at actual wind speed at hub height

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Sound emission measurement according to IEC 61400-11

- Measure the sound pressure level on a hard board on the ground at a distance of the total height of the wind turbine
- Relate the sound pressure level to wind speeds at hub height
- Calculate the sound power level

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Nytänkande med erfarenhet

Sound emission measurement in Ryningsnäs

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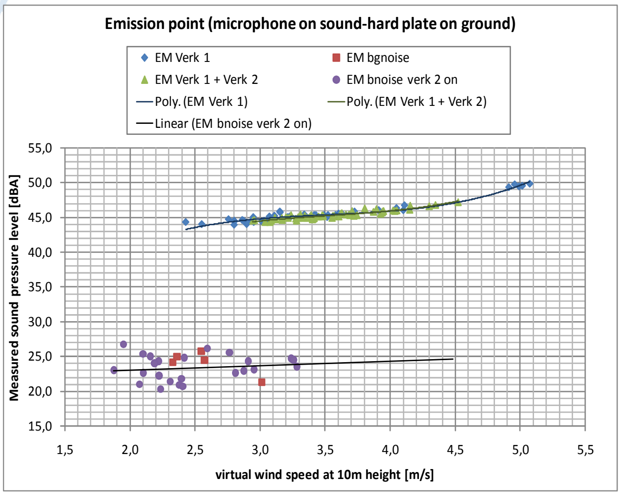
Nytänkande med erfarenhet



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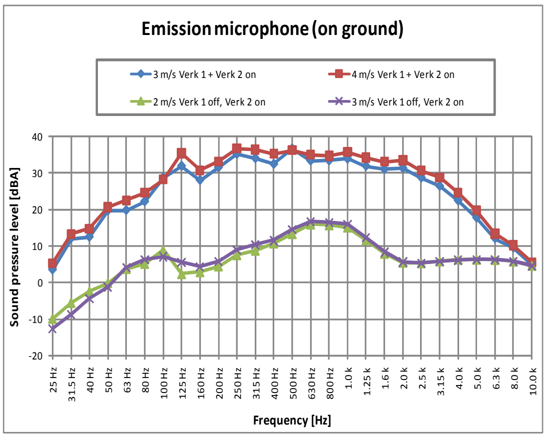
Nytänkande med erfarenhet



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Nytänkande med erfarenhet

Calculation in IEC 61400-11

$$V_s = V_z \left[\frac{\ln\left(\frac{z_{ref}}{z_{0ref}}\right) \ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H}{z_{0ref}}\right) \ln\left(\frac{z}{z_0}\right)} \right]$$

$$L_{WA,k} = L_{Aeq,c,k} - 6 + 10 \lg\left[\frac{4\pi R_1^2}{S_0}\right]$$

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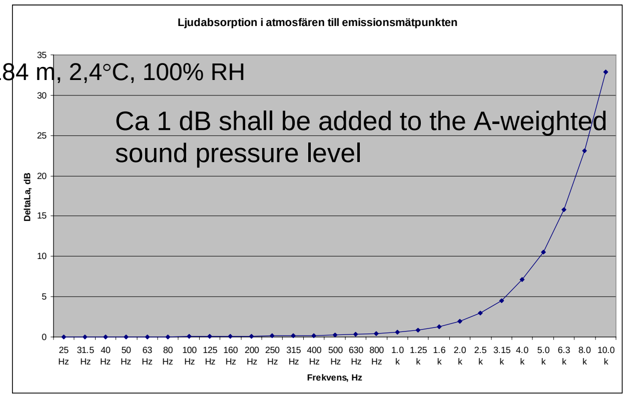
Nytänkande med erfarenhet

Atmospheric sound absorption

- Distance 184 m, 2,4°C, 100% RH

Ca 1 dB shall be added to the A-weighted sound pressure level



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Nytänkande med erfarenhet

Result sound emission measurement

Measured sound power level at 4 m/s at 10 m height at the reference ground roughness 0,05 m $L_{WA,4}$, dB re 1 pW	Guaranteed sound power level at 4 m/s $L_{WA,4}$, dB re 1 pW
96,2	99,0

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Nytänkande med erfarenhet

Result sound power level for prediction of sound pressure level

- 97,8 dBA re 1 pW at 6 m/s at hub height 100 m.
- The attenuation due to atmospheric sound absorption has been added

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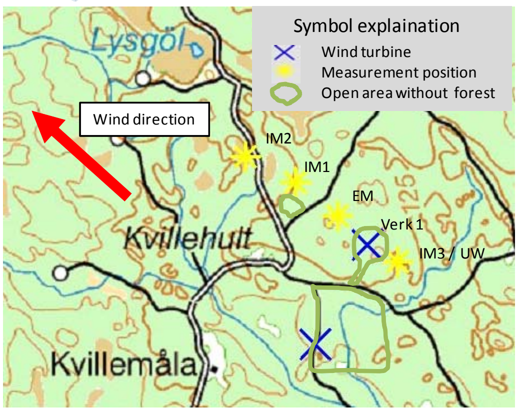
Nytänkande med erfarenhet

Prediction of sound immission from a wind turbine in forest terrain

IM2



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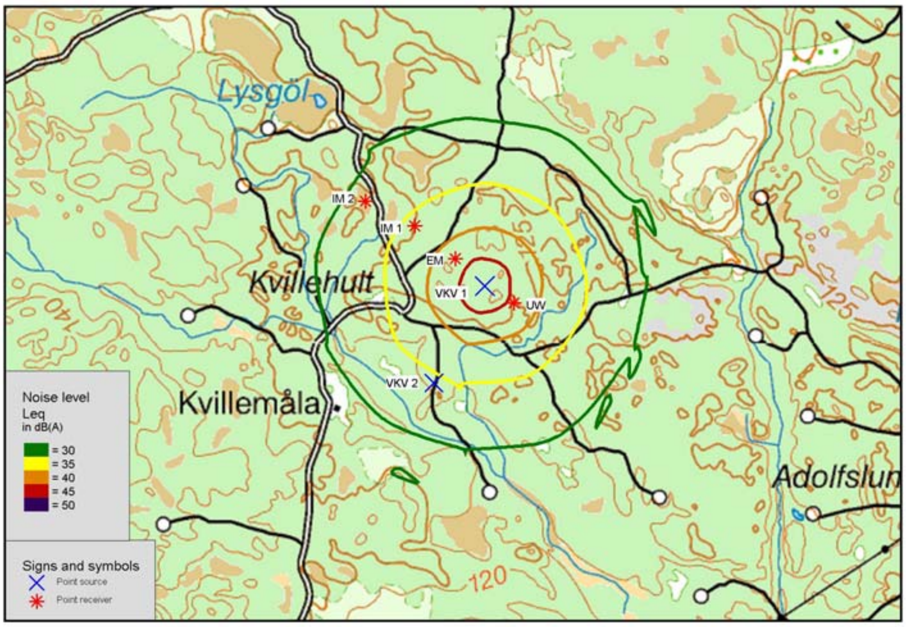
Nytänkande med erfarenhet

Measured compared to calculated with Nord2000

Measurement point	Measured dBA re 20 µPa	Calculated at 1,5 m height dBA re 20 µPa
EM, 150 m on board on the ground	46,5	-
EM, 150 m recalculated to 1,5 m above porous ground	42,2	42,7
IM1, 330 m 1,4 m above ground	37,3	35,9
IM2, 520 m 1,5 m above ground	34,3	31,8
IM3/UW, -125 m 1,3 m above ground	45,8	43,7



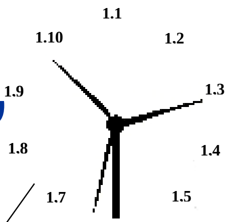
Reason for higher measured than predicted in the forest?

Hypothesis: reverberation

LW measured for point source at hub

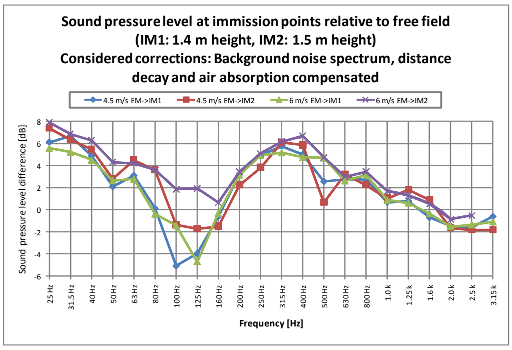
Calculated Nord2000

Guaranteed LW



Measurement point	Variant 1	Variant 2	Variant 3	Variant 4 = 3 but with forest acc. to ISO
IM 1	37,8	36,0	35,9	32,1
IM 2	33,6	31,7	31,8	28,1
EM	44,4	42,6	42,7	39,2
UW	45,3	43,8	43,7	41,1

Measured sound propagation relative to free field



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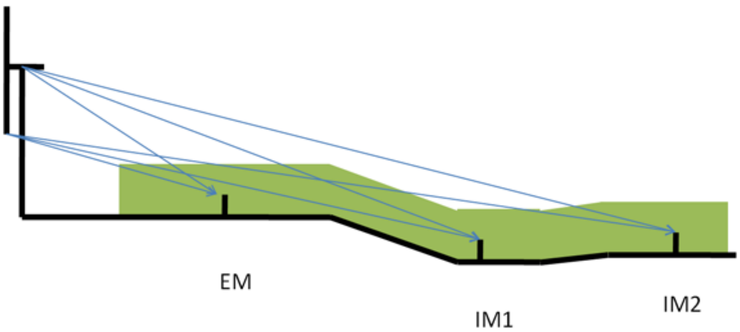
Nytänkande med erfarenhet

Sound propagation in forest with trees



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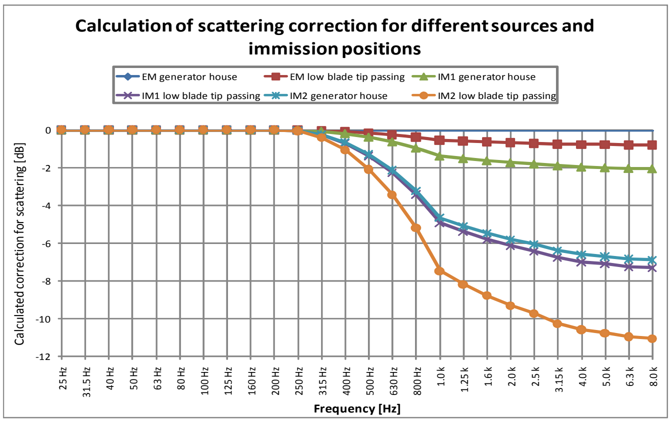
Nytänkande med erfarenhet

Sound attenuation in forest acc to Nord2000



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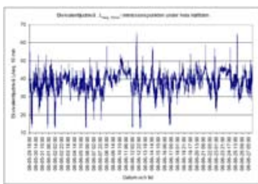
Nytänkande med erfarenhet

Sound immission measurement

- Measurement of sound pressure level at a dwelling can be done according Elforsk report 98:24, which is similar to IEA Recommended practices for wind testing: 10. Acoustics. Measurement of noise immission from wind turbines at noise receptor locations, S. Ljunggren 1967
- The method should be developed to be done as an unmanned longterm measurement to increase the possibility to find the right meteorological window.



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Example sound immission measurement

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Nytänkande med erfarenhet

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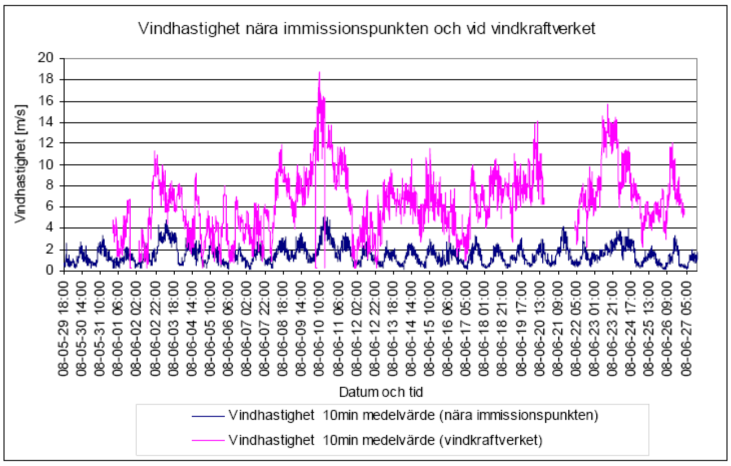
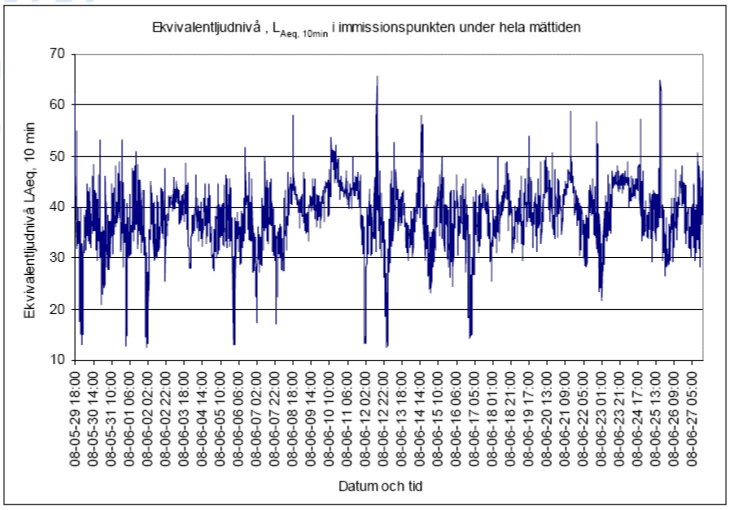
Nytänkande med erfarenhet

Wind speed at the wind turbine and at the immission point



LAeq at the immission point



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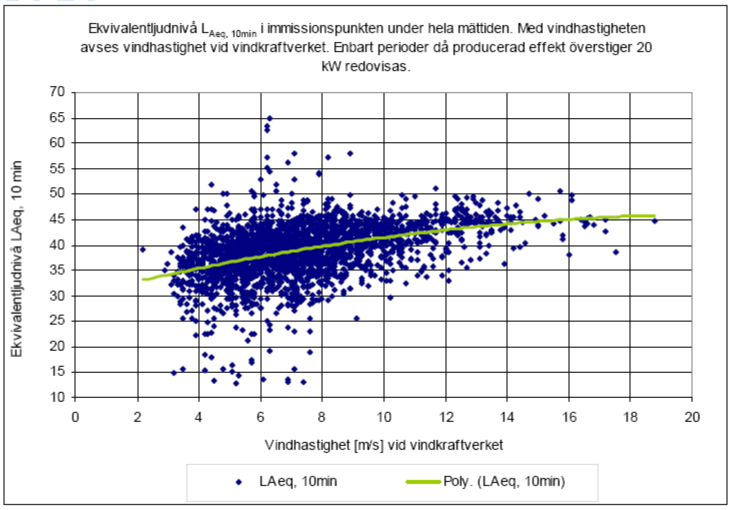
Nytänkande med erfarenhet

LAeq at the immission point



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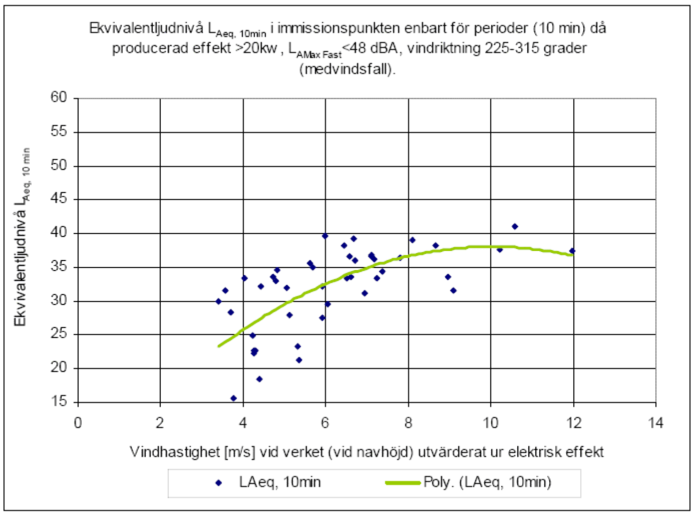
Nytänkande med erfarenhet

LAeq at the immission point sorted



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Nytänkande med erfarenhet

8. Resultat av mätningen enligt Elforsk 98:24, metod B

Frifältsnivån hos det totala ljudet, dvs ljud från vindkraftverket och bakgrundsljud i mätintervallen har med hjälp av Figur 18 bestämts till

$L_{Aeq,free}$ = 38 dB re 20 µPa

Det betyder att enbart vindkraftverket ger en ljudnivå vid bostaden som inte överskrider 38 dBA enligt Elforsk 98:24, metod B. Slutsatsen avser den aktuella mätperioden.

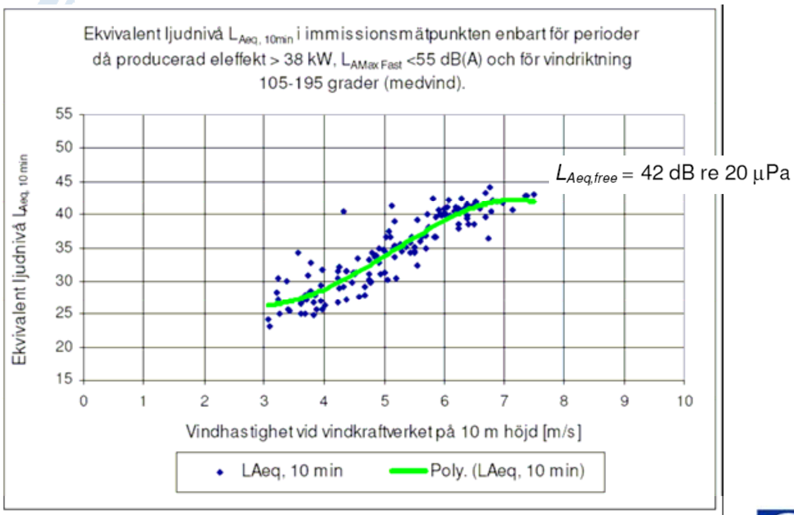
Osäkerheten för ljudnivån mätt med precisionsljudnivåmätaren är mindre än 0,2 dB. Spridningen av ljudnivå i förhållande till regressionslinje vid olika vindhastigheter framgår av diagrammen i rapporten.

Inga toner kunde uppfattas från vindkraftverket

34

Nytänkande med erfarenhet

Another example



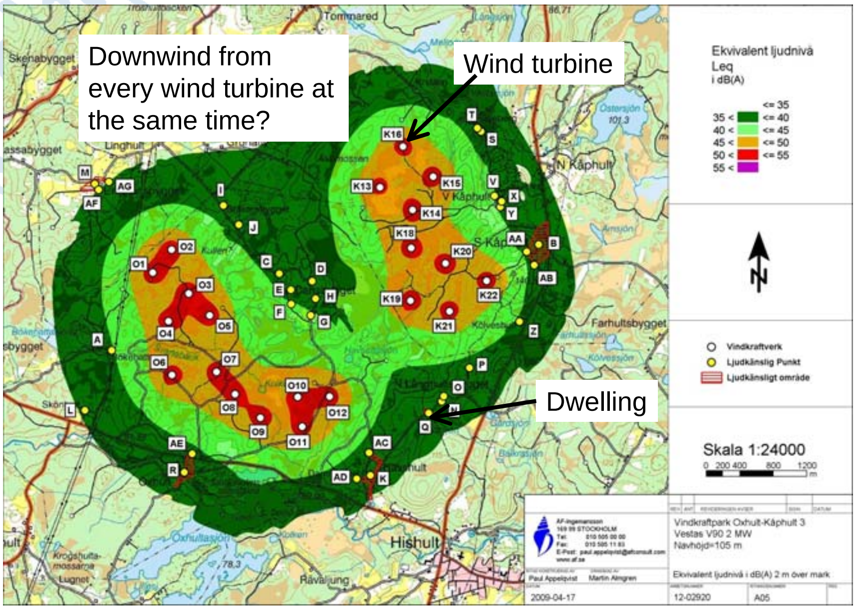
35

Nytänkande med erfarenhet

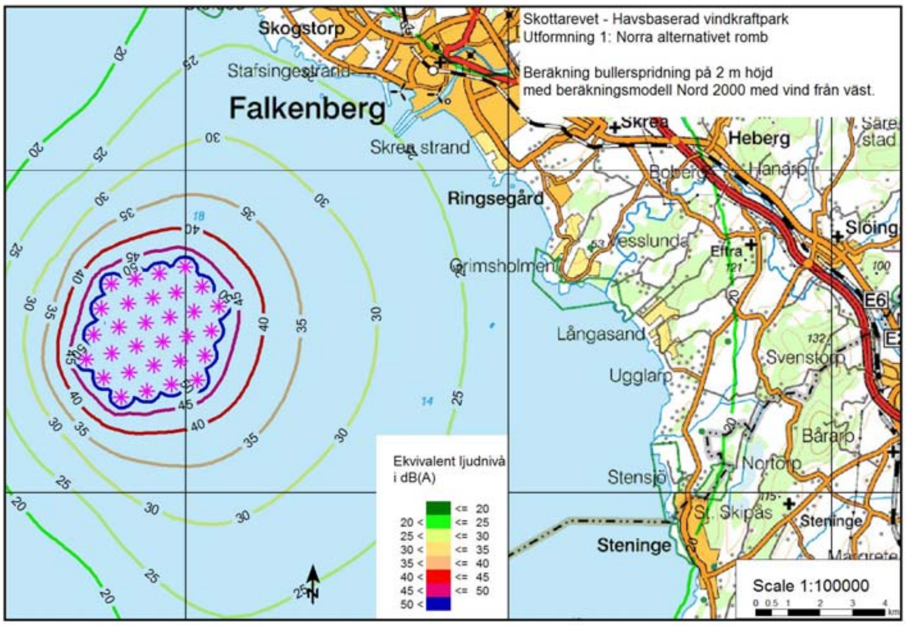
Example of calculated sound immission in Nord2000

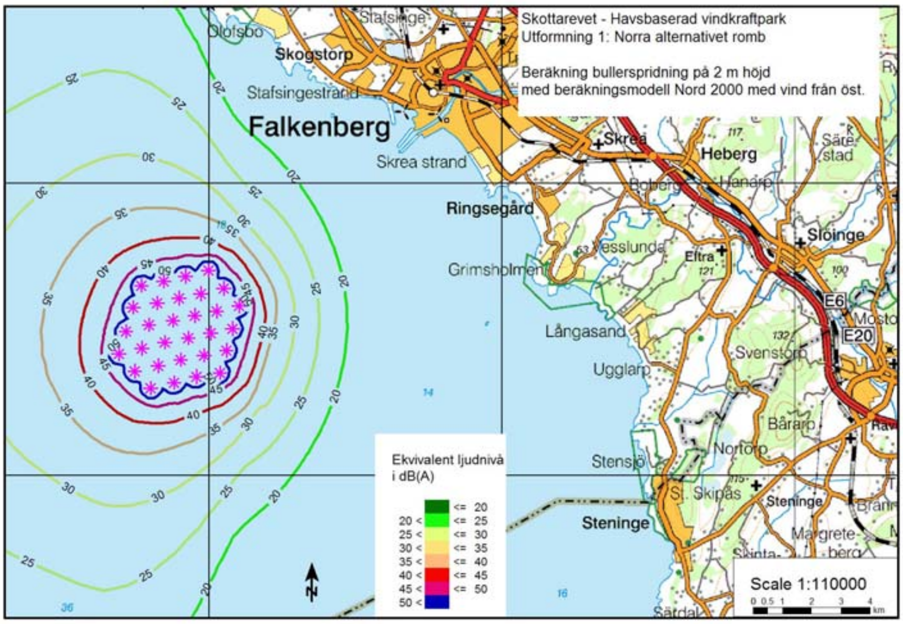
36

Nytänkande med erfarenhet



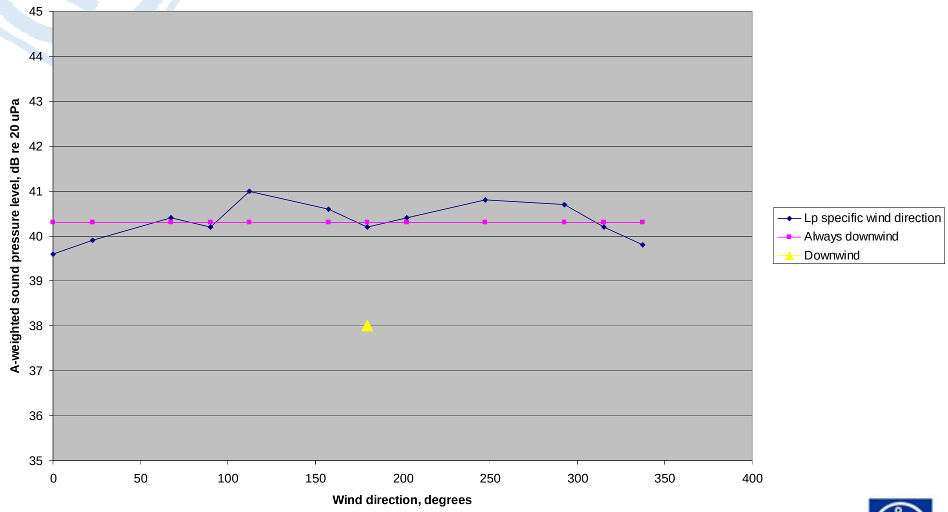
Nytänkande med erfarenhet





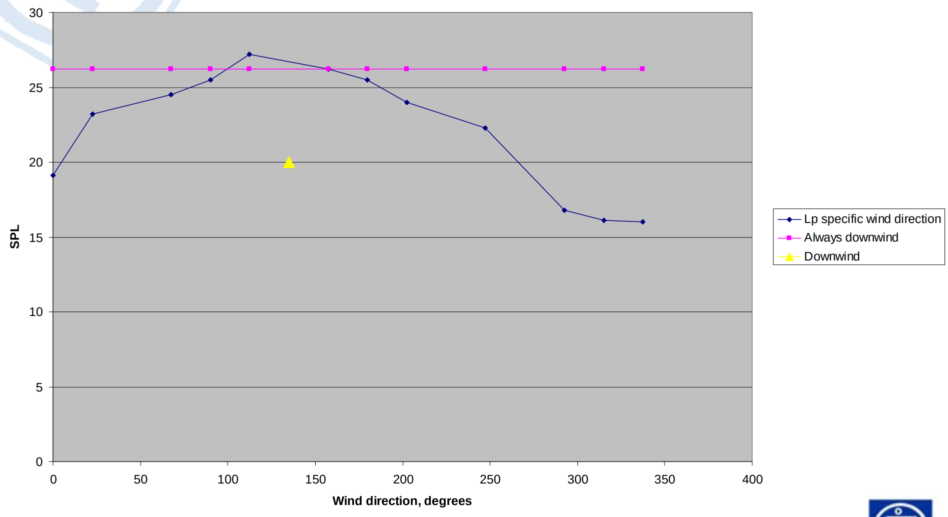
39 Nytänkande med erfarenhet

Calculated sound pressure level at Enskiftet from 6 wind turbines. The closest turbine is approximately 300 m south (180 deg) Enskiftet.



40 Nytänkande med erfarenhet

Calculated sound pressure level at Karlsfält from 6 wind turbines. The closest turbines are approximately 1,3 km southeast (135 deg) of Karlsfält.



41

Nytänkande med erfarenhet

Noise compliance check – New praxis the Supreme Environmental Court in Sweden

- Increased liability for violation of limit values
- Example in MÖD 2009-01-29 M1303-07
- The limiting values shall be stated together with a method to check them

42

Nytänkande med erfarenhet

ÅF-Ingemansson

Leading expertise in sound and vibration

Martin Almgren

ÅF-Ingemansson
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Nytänkande med erfarenhet

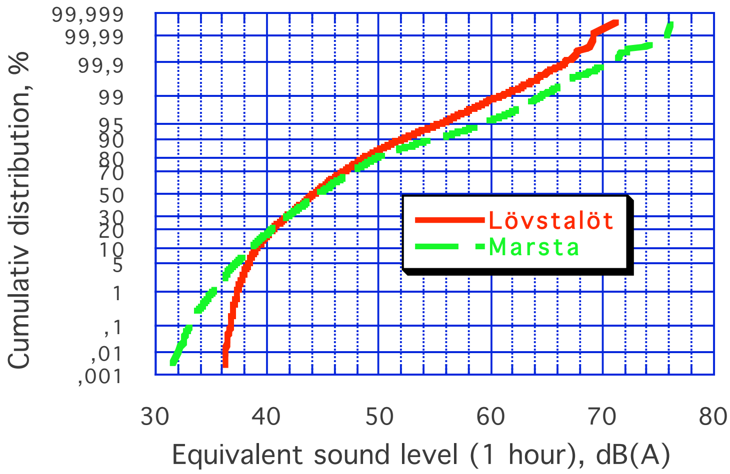
Sound propagation models and validation, IEA

METEOROLOGICAL DATA AND EXPERIMENTS

Conny Larsson

Department of Earth Sciences

Uppsala University, Sweden



Sound propagation models

Models for acoustic wave propagations outdoors give mean values as results, which not necessarily are correlated with health problems.

These models are used for community planning of noise, such as localisation of wind turbines.

The variations due to changing vertical temperature and wind gradients are in a very few cases included in such models, but then only to a very small extent.

The models therefore do not reflect a true outdoor condition. Certain weather conditions change the sound propagation and episodes with time duration from minutes and hours up to days occur with much higher sound levels than the calculated mean values.

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Questions

Which atmospheric processes are causing such episodes?

How is their occurrence and how general are they?

How could they be included in the models so the models show the real outdoor noise level?

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The most important meteorological effects on sound propagation

refraction,

scattering by turbulence

and

atmospheric absorption.

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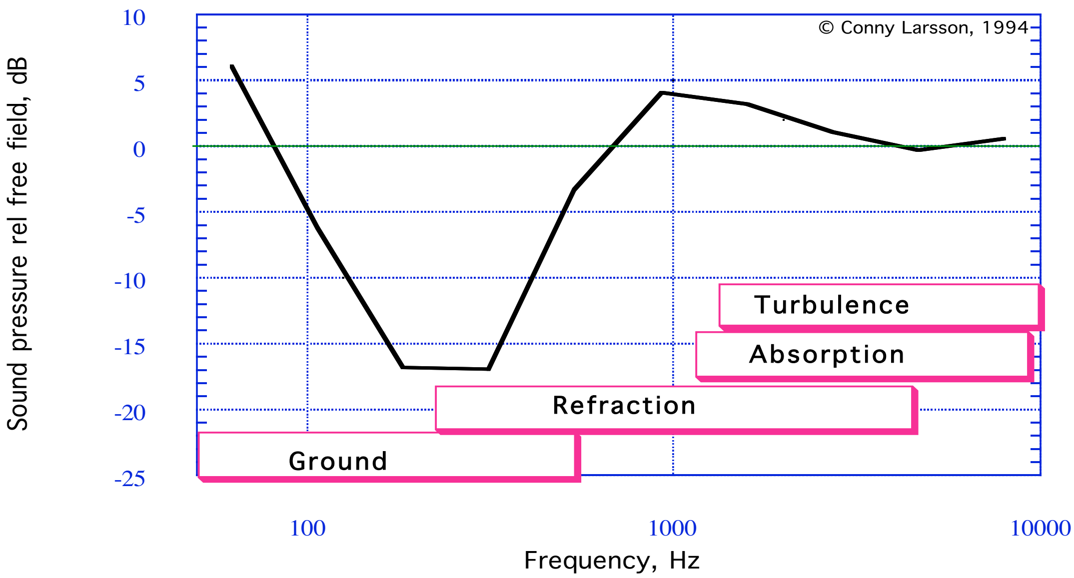

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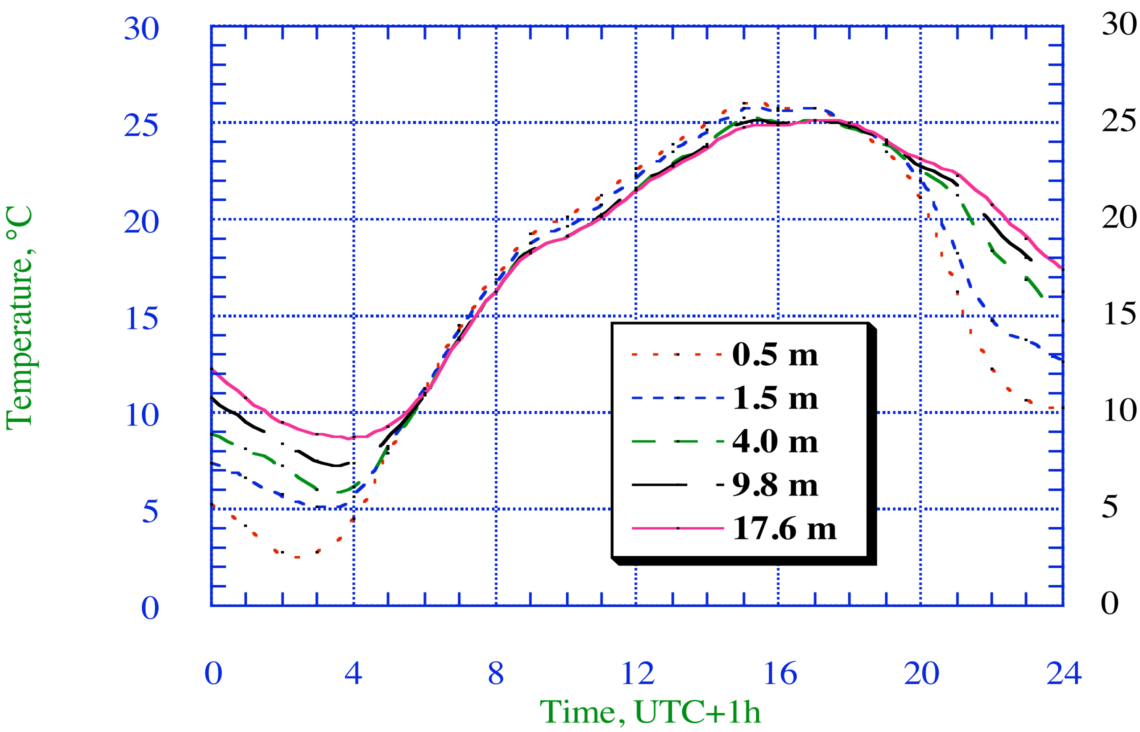

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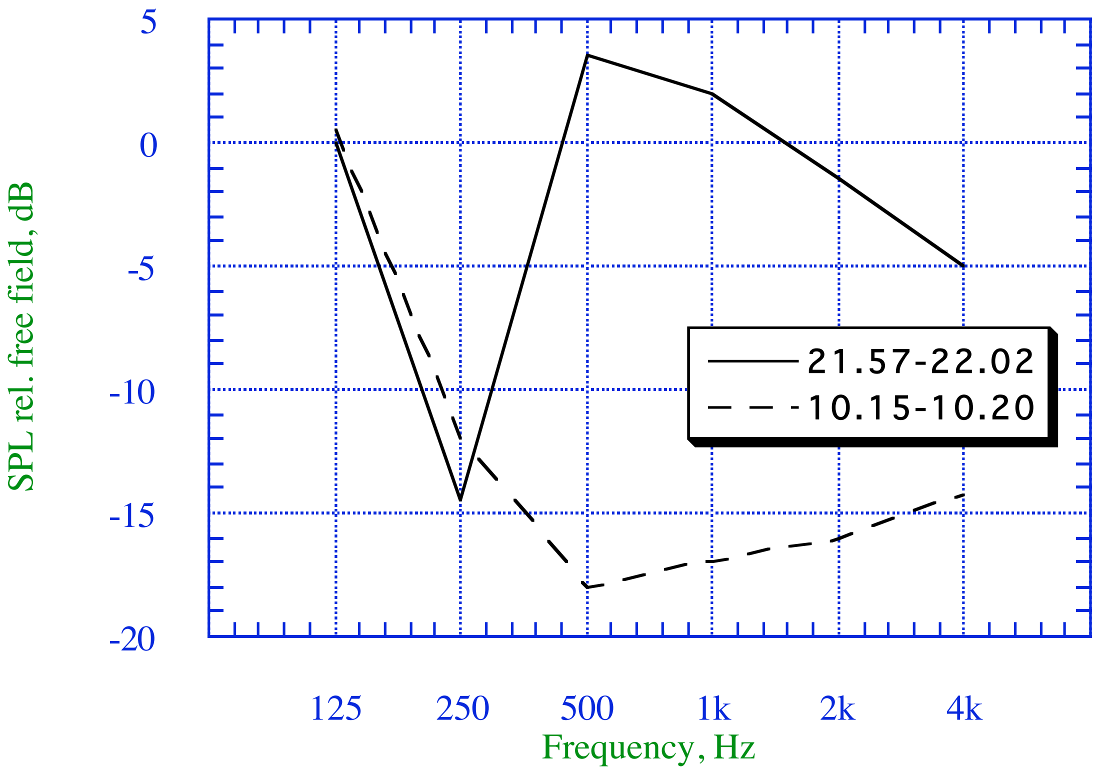

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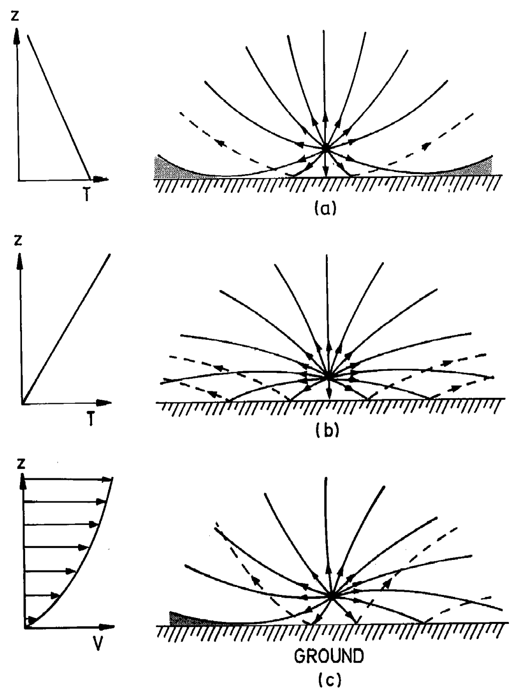
Land
(Sea)

Summer day
(Autumn/
Winter)

Winter morning
(Spring/Early part
of summer)

Down- and
Up-wind



Quite

Noisy

Quite Noisy

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Daily variations

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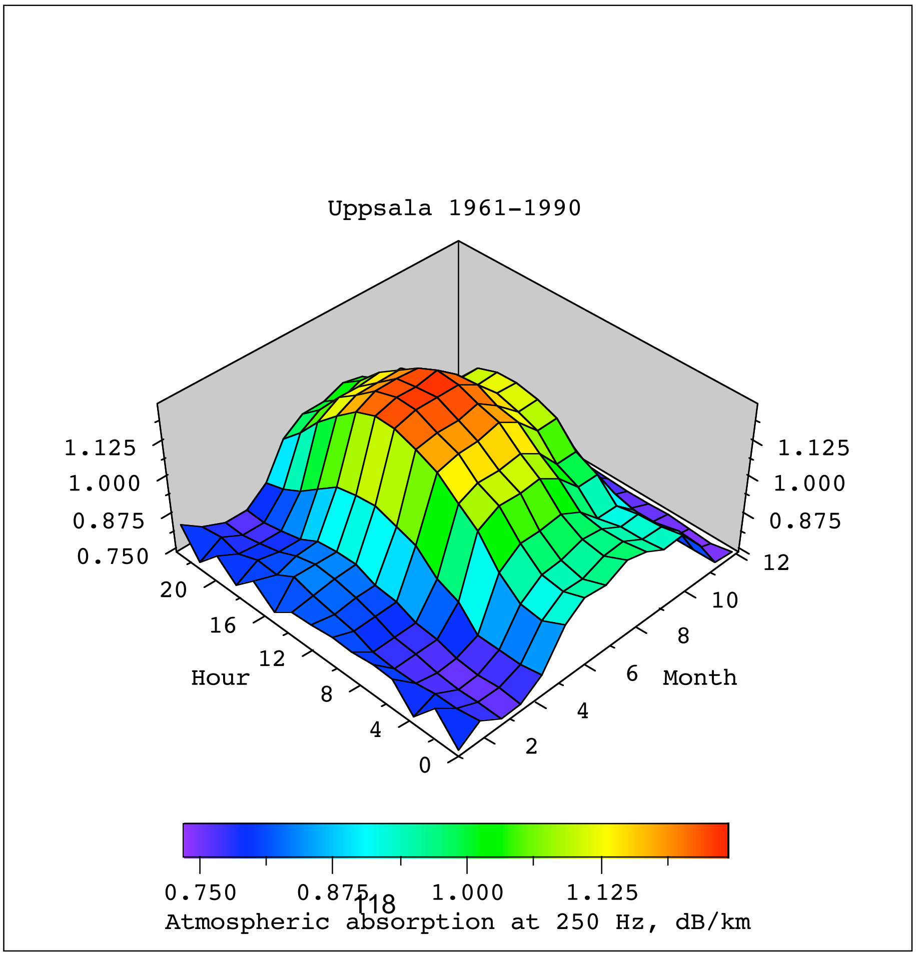
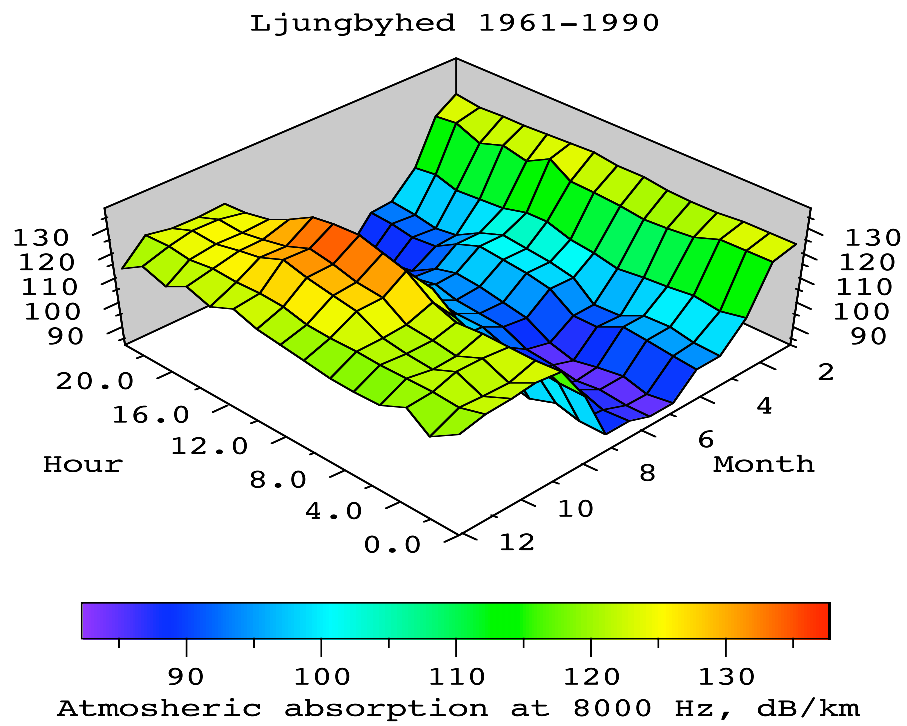
Annual variations

Absorption

Atmospheric absorption depends on frequency, relative humidity, temperature and atmospheric pressure.

The atmospheric absorption increases with distance and becomes more important the longer sound propagation is under study.





Variations in the input data sets!

The atmosphere physic processes cannot be studied separately due to that they interact with each other.

We must therefore study all these parameters simultaneously otherwise with get either under- or overestimation of the occurrence of different sound levels.

Amount of time

Rough estimate

Higher sound levels occur from two hours before sunset until sunrise (14h/24h ≈ 60%) for land based sources.

Modified by cloudiness and wind speed.

For low wind speeds that often exist during night close to the ground the sound propagation is governed more by temperature gradients than by wind direction.

0% (windy place with high amount of clouds; stormy coastal areas)

60% (little amount of clouds; inland locations)

For most places we can estimate the occurrence to15-30% often the time and mostly during nights.

Displaying the sound climate

Most usual today

Meteorological conditions are seldom used as input to the different prediction models.

Mean values, histograms or cumulative distributions.

No information when high sound levels occur.

Sound profiles display sound levels during the day and the year.

Much better tool for planning and decision making.

Clear information about when the high sound levels occur.

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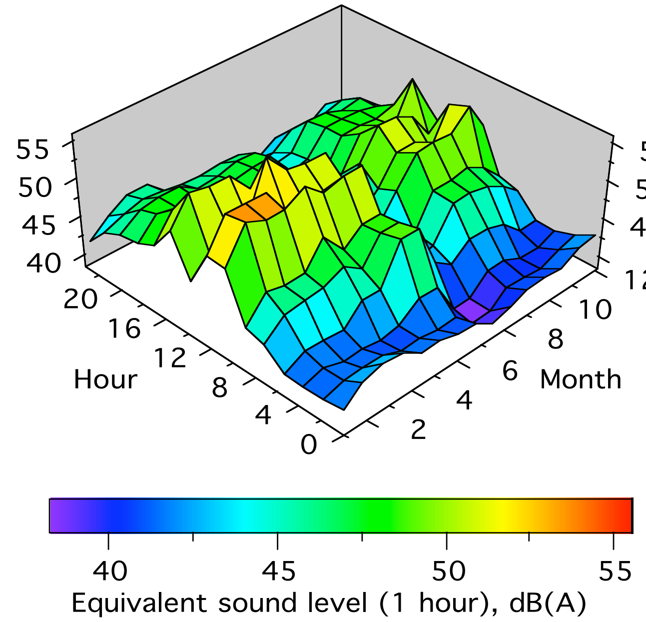

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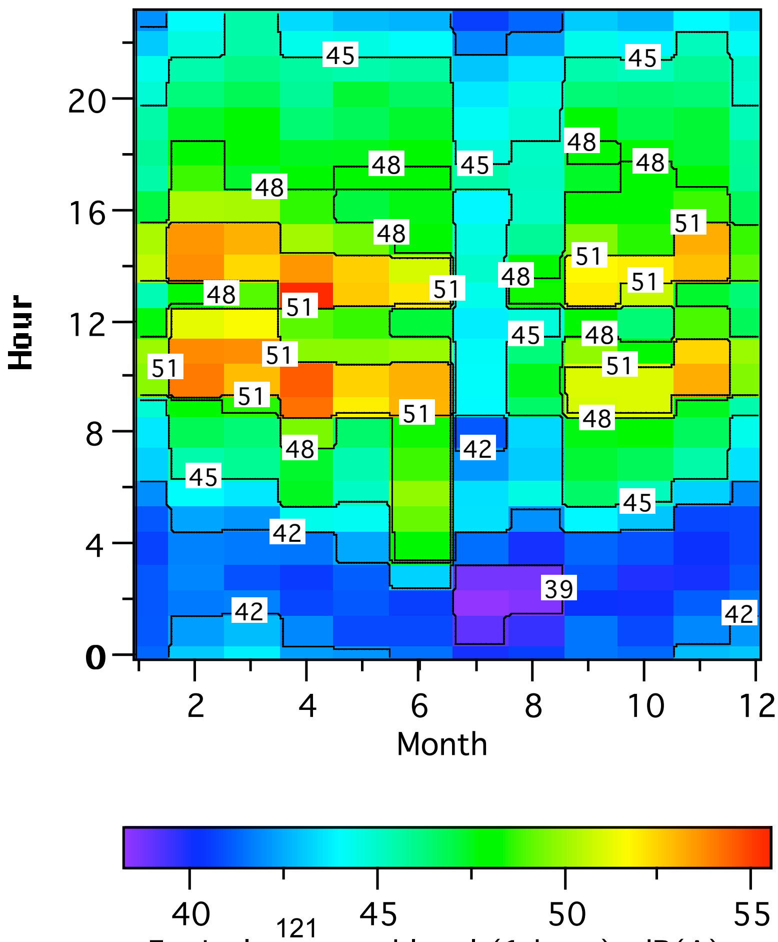

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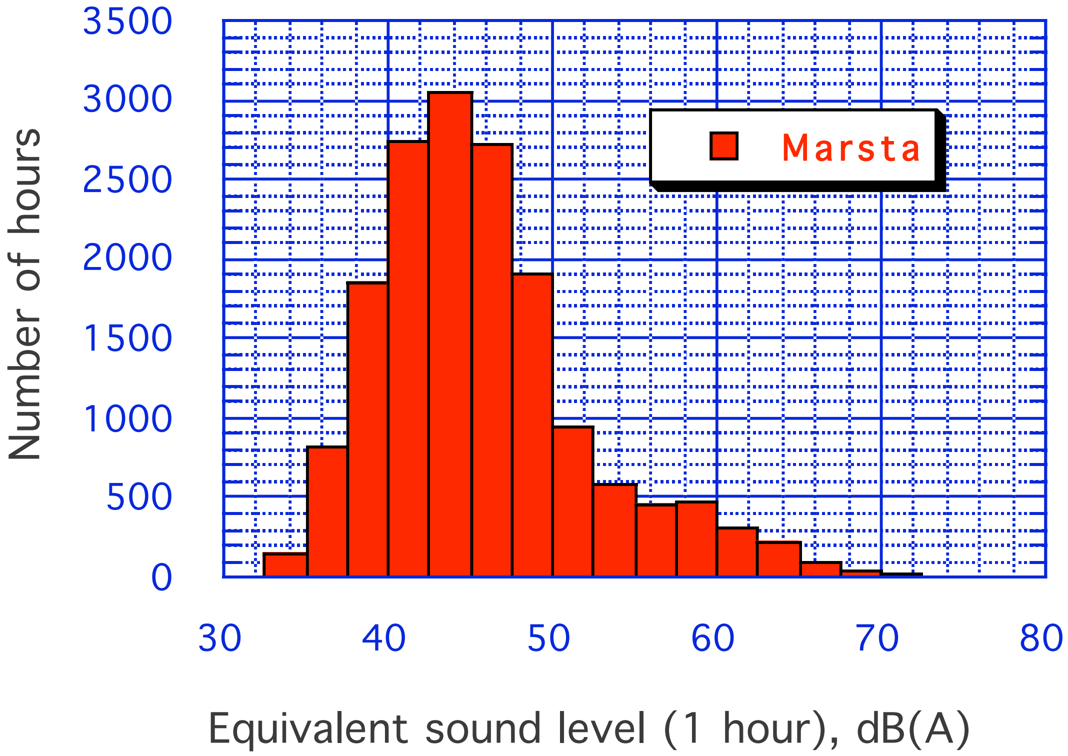

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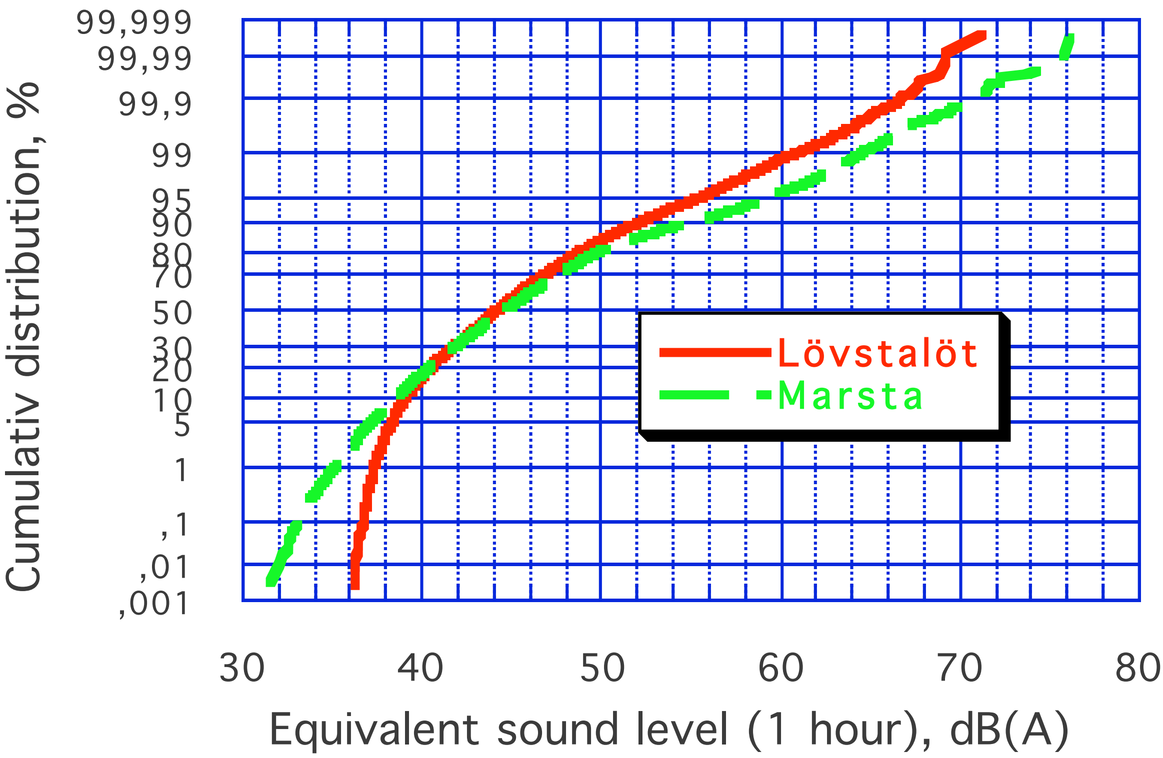

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Conclusions

The weather has a fundamental influence on the sound propagation outdoors.

Sound sources and the weather show variances during the day and the year.

The highest noise levels can disturb and we must calculate how often they occur.

They must be included in the models in order to give the real outdoor noise level distribution.

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Part 1 by ARAKAWA

Chuichi Arakawa, Oliver Fleig, and Makoto Iida
The University of Tokyo

Acoustic Noise Measurement

Takao Maeda
Mie University

IEA Wind Task 11 in Stockholm

Start of Wind Turbine Power Plant in Tokyo

Aim of this work

- To predict using direct noise simulation the aerodynamic broadband noise emitted by a rotating wind turbine blade of arbitrary shape with focus on tip noise
- To clarify physical mechanisms associated with the tip noise that cannot be explained through wind tunnel experiments or outdoor field tests
- To optimize the tip shape and propose noise reducing concepts to increase public acceptance of wind energy

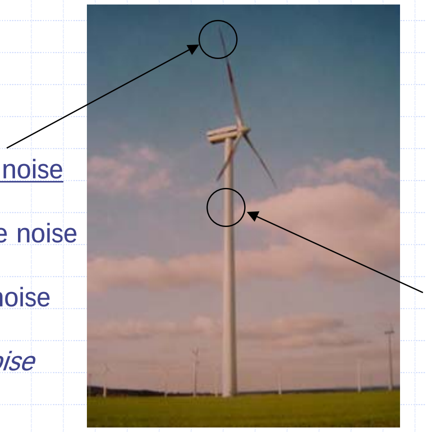
Outline of this work

- Predict the far-field broadband noise caused by the wind turbine WINDMELIII using Large-Eddy Simulation and acoustic analogy
- Simulate 2 tip shapes (actual WINDMELIII tip shape and ogee type tip shape) and investigate the effect of the tip shape on the overall noise level
- The present simulation is the first Large-Eddy Simulation of a full wind turbine blade and the largest simulation of a wind turbine to date, using 300 million computational grid points

Outline of presentation

1. Wind turbine noise
2. Numerical methods
3. Simulation of wind turbine WINDMELIII: Flow and acoustics

1. Wind turbine noise



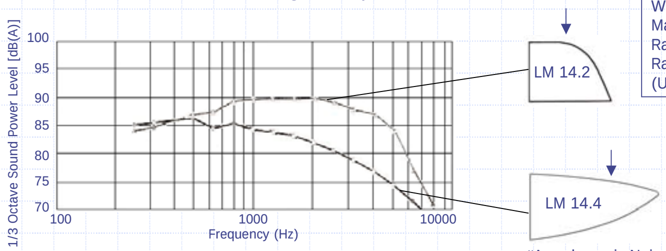
Tip vortex noise

- Aerodynamic broadband noise increases approximately with the 5th or 6th power of the effective flow velocity of the blade section
  - Tip region has highest flow speeds
- A great part of the aerodynamic noise emanates from the outer 10-20% of the blade
  - Strong noise sources at tip
- Field tests have shown that the geometry of the blade tip has a strong effect on the overall noise level
- Trend towards larger wind turbines with increased tip speed ratio
  - Problem of tip vortex noise draws further attention

Outdoor noise measurements

- Noise measurements carried out by DEWI
- Strong effect of tip shape geometry on noise radiation (<u>up to 4 dB</u>)
- Physical phenomena of tip vortex noise are not well understood
  - Turbulence in the locally separated flow region
  - Interaction of tip vortex with the trailing edge of the blade

- <u>**Strong need for numerical prediction:**</u>
  - Understand the physical phenomena causing tip noise
  - Find noise reducing concepts



Wind speed: 10m/s
Ma_{Tip}: 0.18
Rated power: 500 kW
Radius: 18.5 m
(Upwind, 3 blades)

"Aerodynamic Noise from Wind Turbines", DEWI-JOU2-0233-03, Klug, H. and Osten, T. October 1995, German Institute of Wind Energy

WINDMELIII

National Institute of Advanced Industrial Science and Technology (AIST)

<u>Field test:</u>
Very strong vortex/noise source between 3 kHz and 6 kHz at blade tip

Importance of tip vortex noise for future large and fast rotating wind turbines

Noise experiment at AIST

- AIST (National Institute of Advanced Industrial Science and Technology, Japan)
  - Nii et al (2001) measured the noised emitted by WINDMELIII
  - Strong noise source at blade tip (5 kHz)

Parameters of noise measurement experiment

Reynolds number	1.0×10^6
Tip Mach number	0.16
Rotor diameter	15 m
Rotor speed	67.9 rpm
Tip speed ratio	7.5
Power output	16.5 kW
Wind speed	8 m/s

WINDMELIII

Numerical modeling

- Wind tunnel tests and outdoor field tests do not provide sufficient information about the physical phenomena associated with the noise generation
- Strong need for accurate numerical prediction of aerodynamic noise
- Very fine computational grid required to accurately predict turbulent frequency spectra
- Large-Eddy Simulation is a very promising tool for acoustic simulation, but requires enormous computational power and memory

2. Numerical methods

- Large Eddy Simulation (LES) to obtain acoustic sources
  - Compressible Navier-Stokes equations

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x_j}\left(F_j-\frac{1}{\mathrm{Re}}G_j\right)=0 \qquad Q=\begin{pmatrix}\rho\\ \rho u_i\\ \rho E\end{pmatrix}, F_j=\begin{pmatrix}\rho u_i\\ \rho u_i u_j+\delta_{ij}p\\ \rho H u_j\end{pmatrix}, G_j=\begin{pmatrix}0\\ \tau_{ij}\\ -\tau_{kj}u_k+q_j\end{pmatrix}$$

$$\tau_{ij}=\left(\mu+\mu_t\right)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)$$

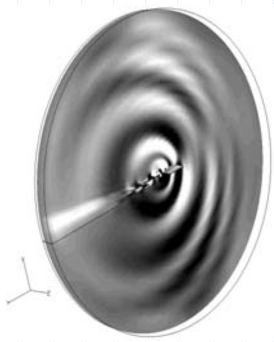
SGS $\mu_t=\rho\left(C_s\Delta\right)^2\left(2S_{ij}S_{ij}\right)^{1/2}$ $\qquad \Delta=\Delta_g\left[1-\exp\left(y^+/26.0\right)\right]$

Smagorinsky Model (Cs = 0.15) Van Driest Wall damping function

- 3rd order upwind finite difference scheme in space
- 2nd order implicit Euler scheme in time with three-point backward differencing for the time derivative (CFL up to 10)

Direct simulation of noise

- Compressible flow solver
  - Can model propagation of acoustic waves
- Near field (1 to 2 chord lengths): LES
  - Need fine grid (smallest wavelength)
  - Accurate modeling of non-linear effects and wall reflection, refraction, scattering in the near field
- Far field : Acoustic Analogy
  - Ffowcs Williams-Hawkings equation
  - Approach by Brentner and Farassat:
    - permeable integration surface which does not need to correspond with the body surface

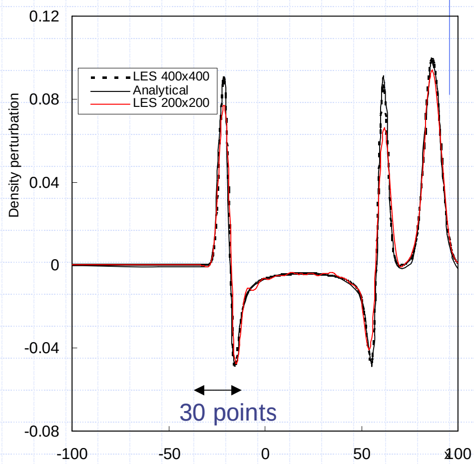


Acoustic pressure perturbation field

Acoustic wave propagation by 3rd order scheme

- Pressure Pulse at (0, 0)
- Simulate propagation
- With more than 400 grid points:
  - Agreement with analytical solution
  - Numerical dissipation is reduced
- Corresponds to 30 grid points per wavelength

Grid spacings in near field are based on these observations: Can model up to 10 kHz in the near field (1-2 chord lengths away from blade)



T = 40

Earth Simulator (Yokohama, Japan)

The Earth Simulator is a highly parallel vector supercomputer system of the distributed-memory type

System Configuration

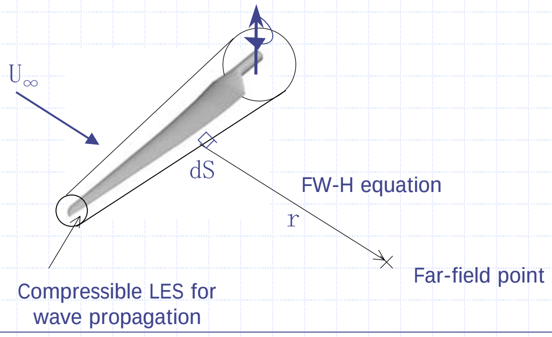
Peak performance/arithmetic processor	8Gflops
Peak performance/processor node	64Gflops
Shared memory/processor node	16GB
Total number of arithmetic processors	5120
Total number of processor nodes	640
Total peak performance	40Tflops
Total main memory	10TB

- 14 nodes (112 Processors)
- 300 Million grid points
  - 99.5 % Vectorization ratio
- 1 time step: 5 seconds
- $\Delta t = 5\times10^{-4}$ (Re. No. $\sim 10^6$, wall resolved)
  - 15 Non-dimensional time units (Noise)
  - 30,000 time steps
  - 1 case : 40-50 hours

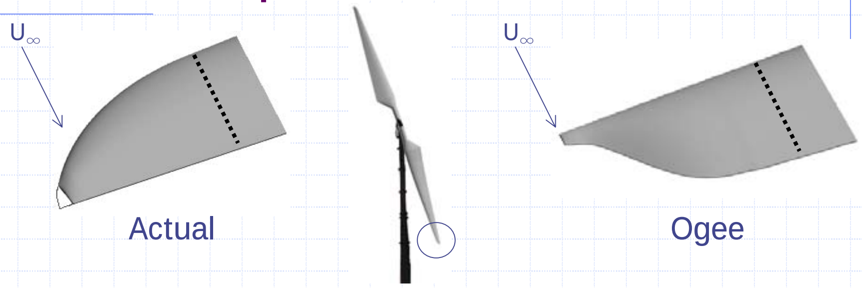
3. Simulation of wind turbine WINDMELIII: Flow and acoustics

- WINDMELIII (AIST) – Wind turbine blade
- Simulation parameters based on noise experiment at AIST
- Near-field LES, Far-field FW-H
- 2 tip shapes analyzed

Method of noise simulation for rotating blade



Simulation parameters

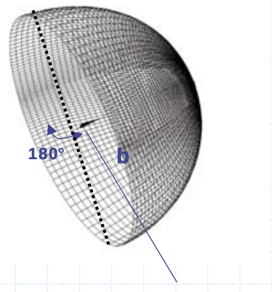


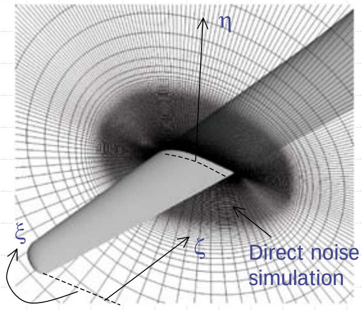
- Rotation included, blade only, no hub
- Rotating frame of reference
- Computational grid
  - 765×193×2209 = 300 million grid points
  - y^+=1 (wall resolved)
  - Spanwise LES requirements only satisfied in the tip region
  - Direct numerical simulation of noise 2 chord lengths away from blade

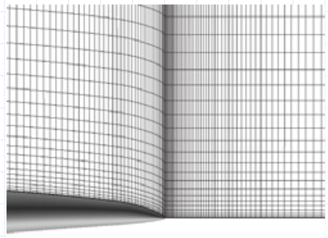
Reynolds number	1.0×10^6
Mach number	0.16

Computational domain and grid

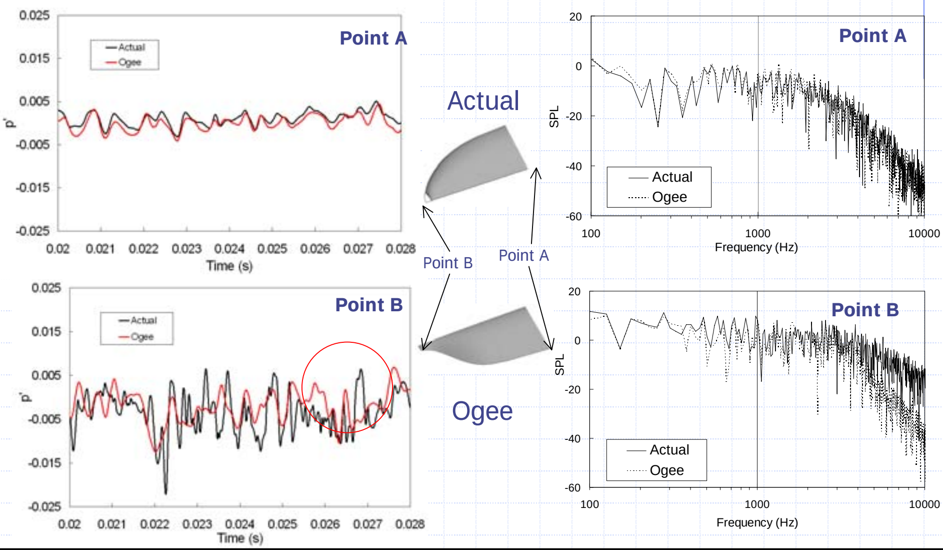
- Single grid
- 2 blades (180 degrees)
  - Half-sphere
  - Periodic a-b
- Rotation about x-axis
- Radius of sphere is twice the blade span
- High concentration of grid points in the blade tip region





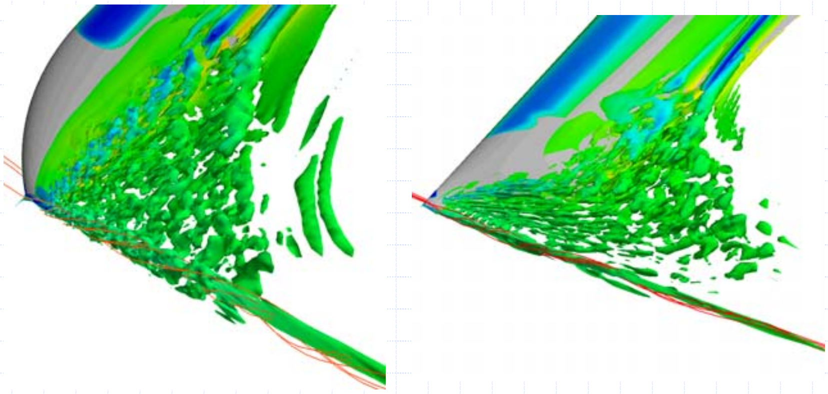


Pressure perturbation near blade tip



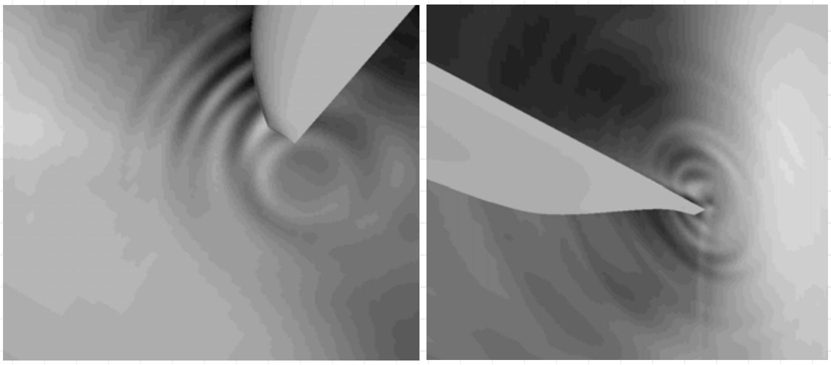
Vorticity isosurfaces ω_x

Actual tip shape Ogee tip shape

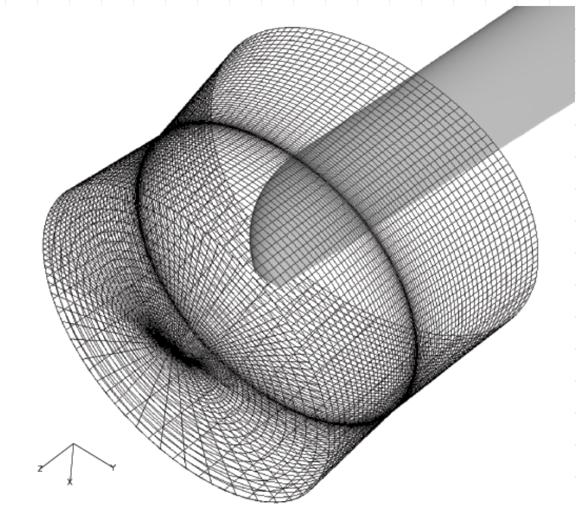


Pressure perturbation field

Actual Ogee



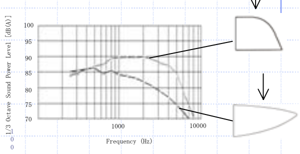
FW-H integration surface

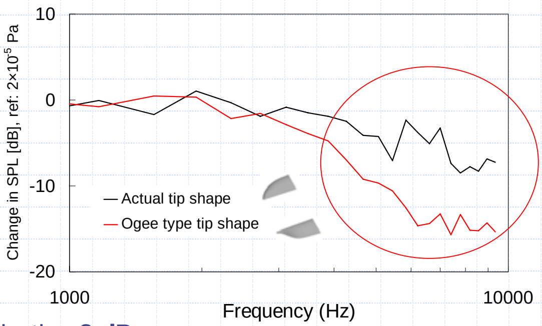


Effect of tip geometry on noise

- Far-field broadband noise by FW-H equation
  - Integration surface is 1.5 chord lengths away from blade
  - Far-field observation point is 20 m upwind of the center of the blades
- Experiment: noise sources at tip from 3 kHz to 6 kHz
  → Similar trend with DEWI measurements

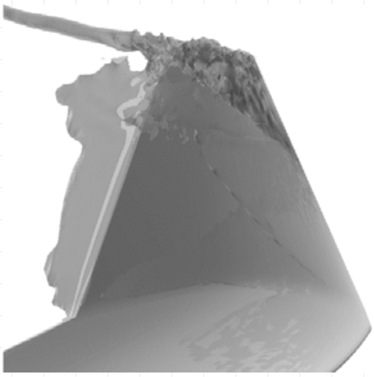
Outdoor wind turbine measurements
DEWI

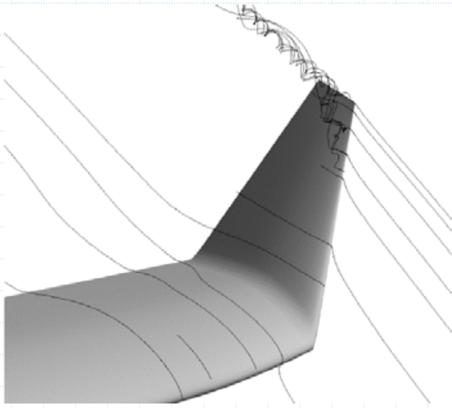




→ Overall reduction **2 dB**

Winglet simulations





Conclusion

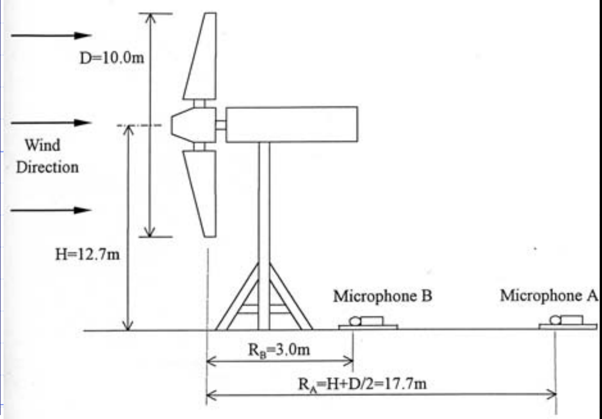
- Developed an aeroacoustic method to study the acoustics emitted by a wind turbine blade of arbitrary shape
- Simulated aerodynamic broadband noise emitted by a rotating wind turbine blade WINDMELIII using compressible LES in the near field and Ffowcs Williams-Hawkings equation in the far field on Earth Simulator, using up to 300 million grid points
- Investigated the effect of the blade tip geometry on the overall noise level

  → Similar trend with noise measurement experiment
  → Decrease in acoustic emission observed for ogee type tip shape

Future work

- Further analysis of physical phenomena and turbulence dynamics related to tip vortex and detailed investigation of acoustic wave propagation in the tip region:
  - → Why does the blade with a cut trailing edge lead to noise reduction?
- Prediction of aerodynamic performance
- Quantitative comparison of the emitted noise with experimental data
- Investigation of noise reducing design concepts such as blade sweep, winglets and trailing edge treatment.

Acoustic noise measurement



Rotor diameter: 10 m

Rated power: 30kW

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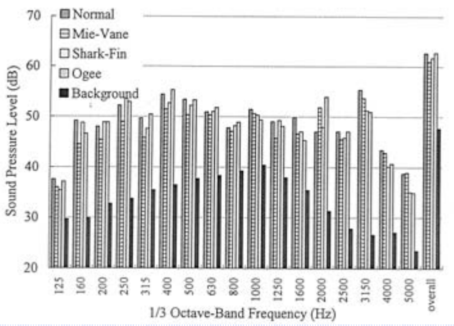
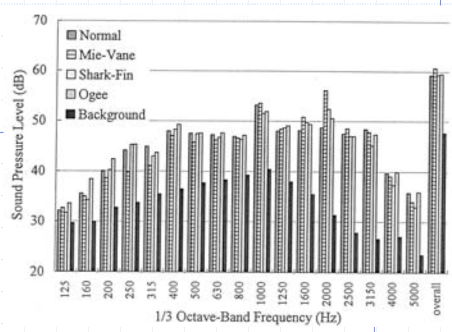
Effect of blade tip shape on noise



Position B
(Close to the tower)



Position A
(H+D dowinwind position)

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1

Infrasound trouble ?
Depress of wind power development ?
Necessity of scientific evaluation

2

Is Infrasound Fatal for Popularization of Wind Power in Japan ?

- Newspapers like to report infrasound problem of wind turbines.
- It is not clear whether infrasound has strong influence for environment.
- Our society has just started research of infrasound of wind turbine.
- SUBARU machine is not the target of trouble reported in the newspaper, and one example of advanced evaluation.

Part 2 by ARAKAWA

2009.5.4
IEA Wind Task 11 Noise in Stockholm

Infrasound Measurement for SUBARU80/2.0

Shigeo YOSHIDA and Soichiro KIYOKI
(Fuji Heavy Industries, Ltd(SUBARU))
Presented by
Chuichi ARAKAWA (Univ. of Tokyo)

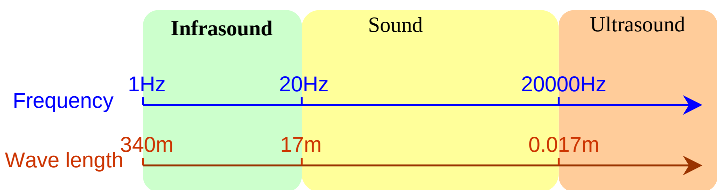
3

4

Background ～What is Infrasound?～

Physical Quantities

Pressure Fluctuation



Infrasound in Daily Environment

Specification	Sound Level [dB(G)]
Commercial Area	76 (60～ 93)
Habitant Area	69 (55～ 91)
Industrial Ares	78 (68～ 89)
Around Motorway	82 (66～ 90)
Around General Road	80 (67～ 97)
Around Railway	84 (72～100)
Around Shin-Kansen	100 (96～103)

From A. Nakano "Infrasound "

Effect

a) Secondary noise

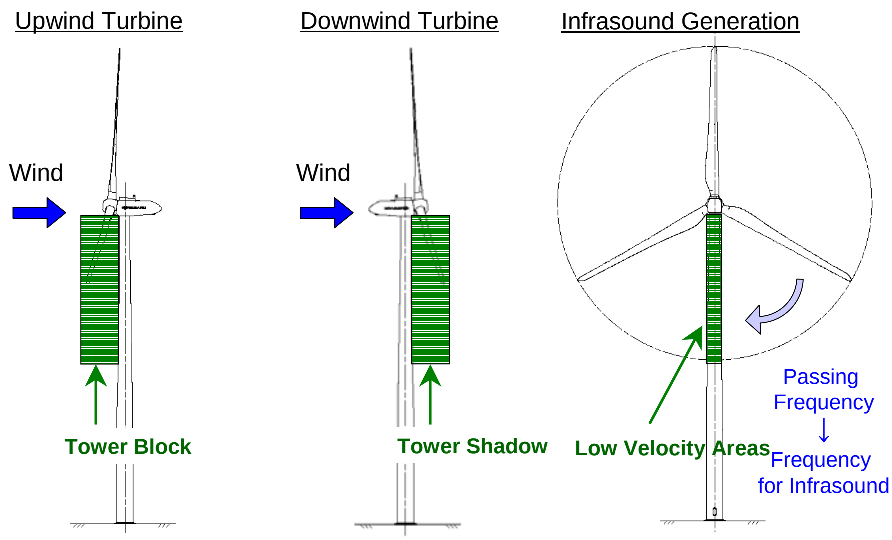
Vibration of furniture

b) Influence for human body

Feeling of oppression

→ Quantitative Evaluation

Background～Infrasound from Wind Turbine～



Background
～Previous DW machine and SUBARU80/2.0～

MOD-1, NASA/DOE, USA, 1979

This machine has impressed us that DW generates strong infrasound.

Decrease of rotor speed
↓
Dissolve of infrasound

SUBARU80/2.0, JAPAN, 2005

First DW machine(2MW)	Characteristics	First commercial DW machine
2 blades → large rotational speed	Blade	3 blades → small rotational speed
Truss structure	Tower	Mono-pole
Small→ large influence of tower shadow	Clearance	Large→ small influence of tower shadow

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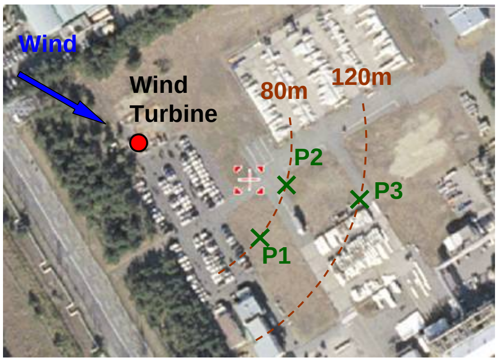
Measurement ～Outlines～

Site ： Wind power of HITACHI KASEI (Kamisu, Ibaragi)SUBARU 80/2.0



※ Yahoo! Mapより引用

Rotor diameter	80 m
Hub height	80 m
Rated power	2 MW
Power control	Pitch
Speed control	Variable
Rotor speed	11-19.5 r/min

Date and Time of Measurement

2008/01/24
Day time （12:00～13:00）
Night time（19:00～21:00）

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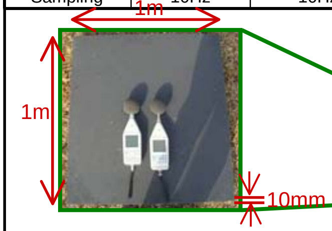
Measurement ～Method～

Operating condition

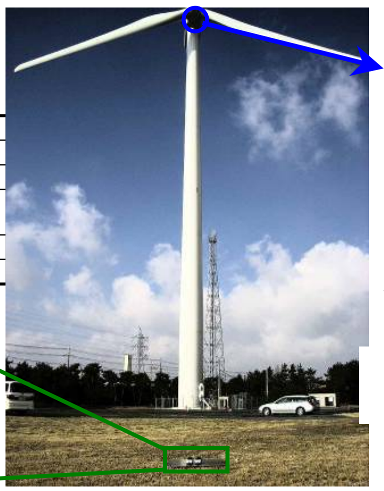
Operation and stop by turns
→ Correction of background noise

Measurement equipment

	Noise	Infrasound
Equipment	RION NA27	RION NA18A
Range	20-12,500Hz	1-100Hz
Freq. Characteristics	FLAT	FLAT
Response	FAST	SLOW
Sampling	10Hz	10Hz



Test Setup View



Velocimeter

Correction of wind speed

Velocity in nacelle
↓
Nacelle⇔Mast Correlation (Prototype)
↓
Velocity for hub

Results ～Frequency Characteristics～

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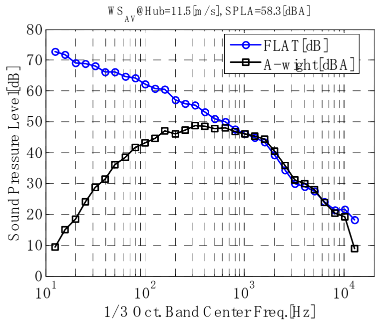
Data details

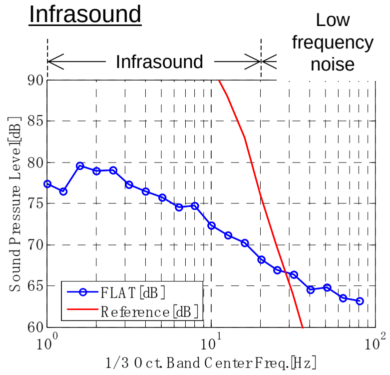
Wind speed	11.5m/s（Hub）
Data processing	1 minute average
Measurement point	Downwind 80m

Noise



No peak appears in some specified frequency

Infrasound



3P：about 0.9Hz, no appearance of peak > 1Hz

Comparison with reference data by Ministry of Environment

- Infrasound : smaller than reference data
- Low frequency : larger than reference data ⇒ Evaluation of noise

Results ～Infrasound, Characteristics of Wind Speed～

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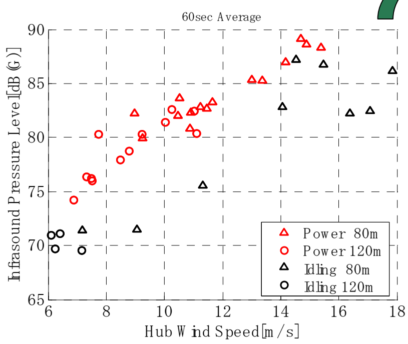
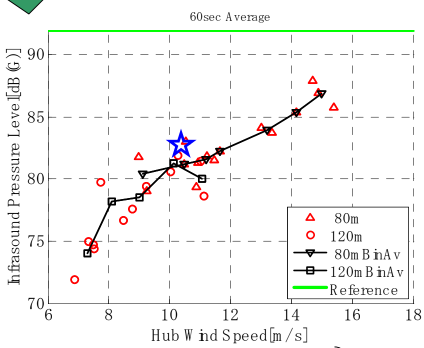
Correction for background noise



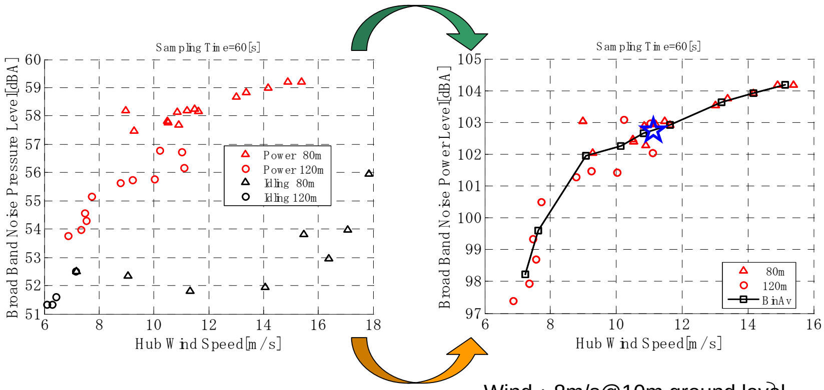


Wind：8m/s@10m ground level
Location：80m down wind
} **82dB(G)**

（Reference by Ministry of Environment :92dB(G)）

Results
～Noise, Characteristics of wind speed～

Correction for background noise



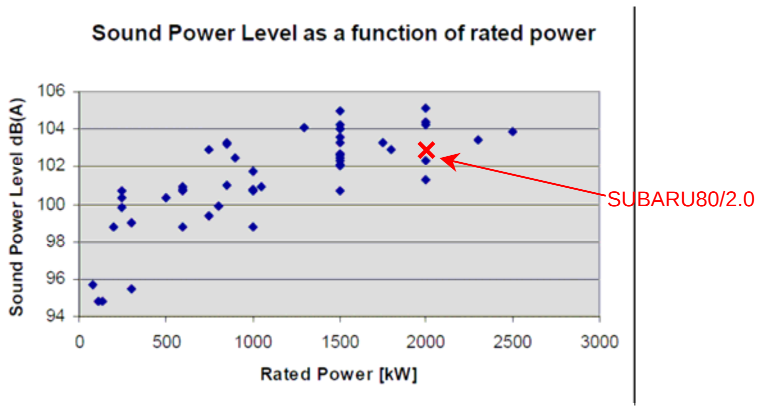
Conversion of power level

Wind：8m/s@10m ground level
Location：80m down wind

102.8dB(A)

$$L_{WA} = L_{PA} - 6 + 10\log\left[\frac{4\pi R_1^{\,2}}{S_0}\right]$$

Results
～Noise, Comparison with other turbines～



【Reference】
Helmut Klug, A Review of Wind Turbine Noise,
First International Meeting on Wind Turbine Noise, 2005.

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Conclusions

Outlines

- The number of publications is small for infrasound measurement of wind turbines.
- Infrasound and noise were measured for 2MW downwind type of turbine, SUBARU80/2.0, with the standard of IEC.

Measurement results

- Infrasound

  Measurement of 82dB(G) is significantly smaller than 92dB(G) of reference value in ministry of environment. Infrasound is not thought to be fatal as far as SUBARU80/2.0.
- Noise

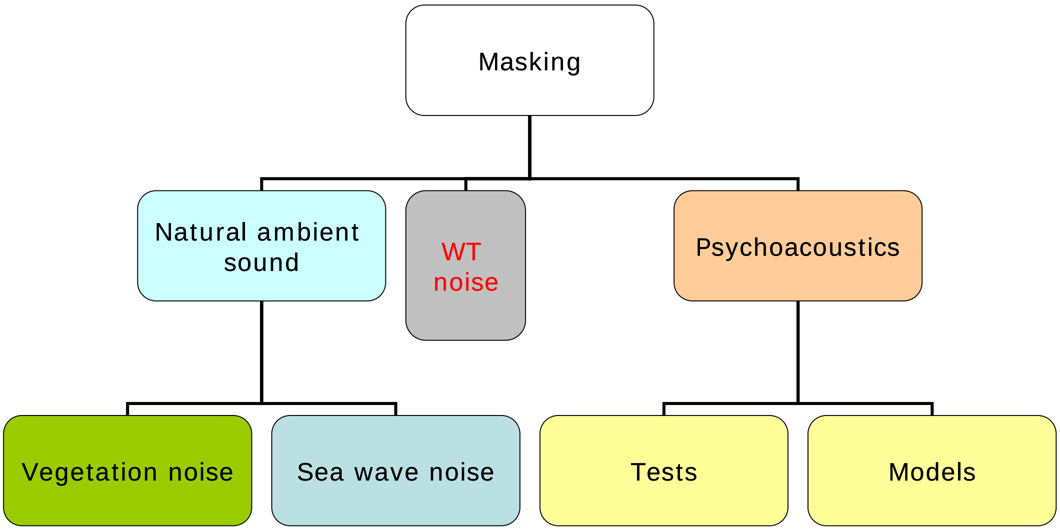
  Noise power level of 102.8dB(A) was measured from the data at 102m downwind with wind speed 8m/s of 10m height. SUBARU 80/2.0 is the same level as others in the noise.

Models of natural background noise and masking of wind turbine noise

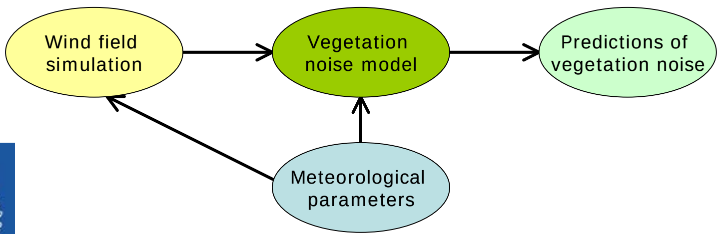
Karl Bolin, KTH, Sweden

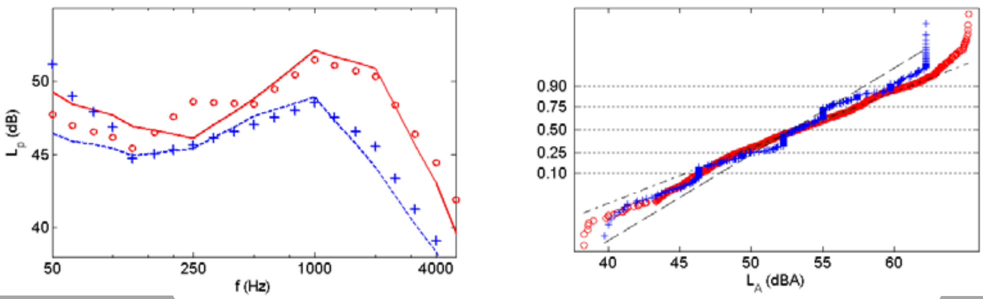
Motivation

- Natural ambient sounds influence the perception of WT noise
- WT noise emission is determined by background in e. g. Britain



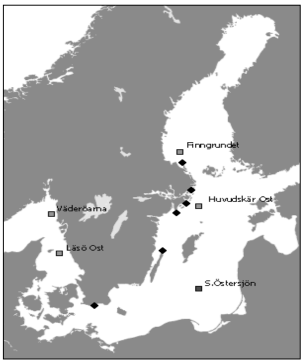
Vegetation noise

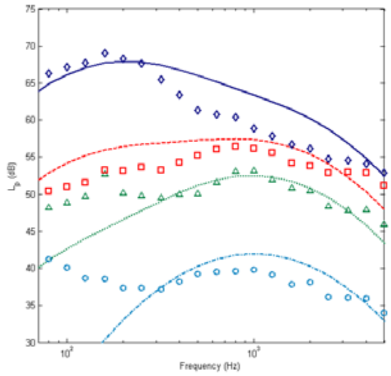




Sea noise model

- Adjust WT noise level wrt sea sound
- Measurements around the Baltic Sea, Wave buoys
- Breaker types
- Similar spectral content as underwater noise
- Semi-empiric model





Psycho acoustics

Loudness models

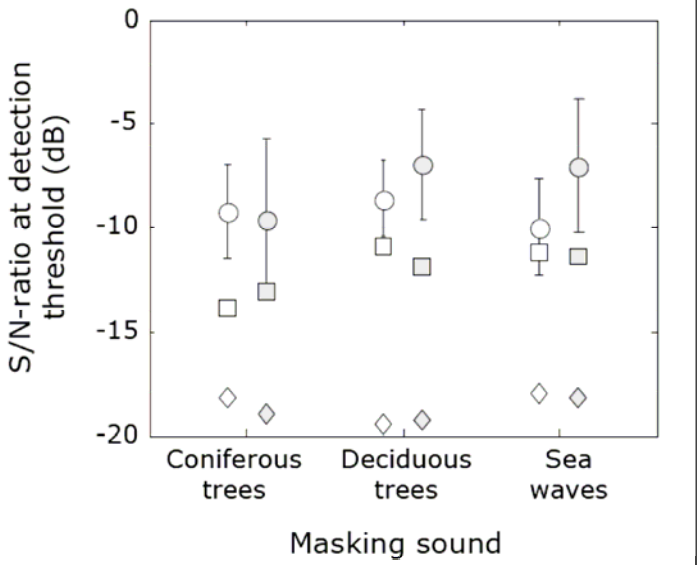
- Predicts both thresholds and partial loudness
- Loudness model by Moore et al[1], Cambridge University
  ANSI S3.4-2007 standard, steady sounds
- Loudness model with time varying sounds
  Glasberg et al[2], Cambridge University

1. B. C. J. Moore, B. R. Glasberg and T. Baer: A Model for the prediction of thresholds, loudness and partial loudness. Journal of Audio Eng. Society, **45**, 224–240 (1997).
2. B. R. Glasberg and B. C. J. Moore: Development and Evaluation of a Model for Predicting the Audibility of Time-Varying Sounds in the Presence of Background Sounds, Journal of Audio Eng. Society, **53**, 906-918 (2005).

Psycho-acoustic test

- Empiric thresholds
  - 3 background sounds, 2 WT noises
  - 50% probability of hits
  - 4AFC method of adjustment, d'=0.84
- Partial loudness
  - Loudness matching
  - 40 dBA masking noise
  - Method of adjustment

Thresholds



ASA/EAA Paris 3rd July 2008

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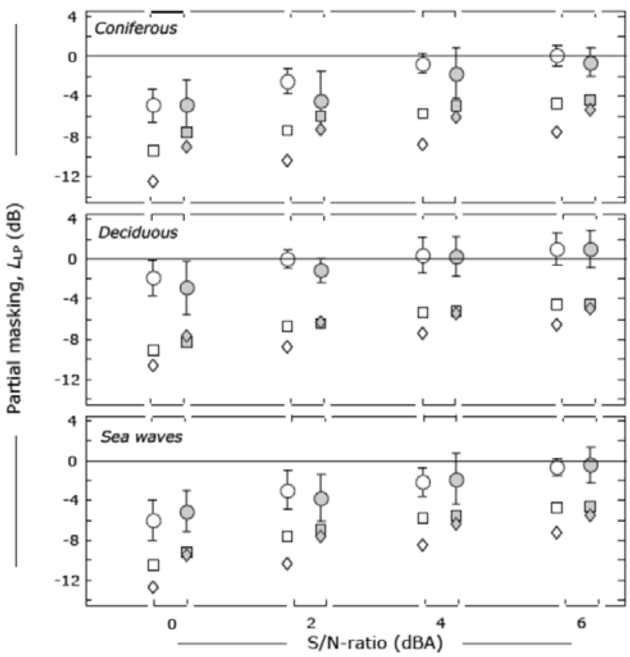
Partial loudness



Conclusion

- Vegetation noise model show good spectral and temporal resemblance to measurements
- Sea noise model could be used in coastal areas
- Not good resemblance between psycho acoustic models and tests, informational masking

Future work

- **Annoyance**
- Auralization

Summary of IEA RD&D Wind – 58th Topical Expert Meeting on:

Sound Propagation Models and Validation

May 2009, Stockholm, Sweden

Félix Avia & Mariano Aristu, CENER
Sven-Erik Thor, Vattenfall

BACKGROUND

For the Wind Farms noise generation and emission, an important work has been performed in the last years, with the development of the existing IEC standards (61400-11: Acoustic noise measurement techniques). However, on the immission side, that is, the calculation of noise levels and measurement and assessment of noise at receptor locations, less has been done and no generally accepted procedures for estimating the noise immission exist.

The objective of this meeting was to report and discuss noise issues, which potentially can be a barrier to the social acceptance of wind energy implementation.

PARTICIPANTS / PRESENTATIONS

The meeting was attended by 17 participants representing 9 countries: Denmark, Finland, Germany, Italy, Japan, Norway, Spain, Sweden and the United Kingdom. The participants represented universities, research centres, public organizations and industries. Presentations covered the following topics:

- Long range sound propagation in the atmosphere
  - Modelling
  - Experimental investigations
  - Offshore Wind Farms
  - Meteorological data
- Background noise (wind driven)
- Masking of wind turbine noise

A total of 13 presentations were given:

1. Different approaches on noise limits,
   Sabine Schulz, ENERCON GmbH, Germany (SSz)
2. A critical look at the wind turbine noise regime in Norway,
   Sigurs Solberg, Norway (SSg)
3. Measuring and calculating turbine noise immission in the Netherlands,
   Seppe Hoogzaad, The Netherlands (SH)
4. Wind Turbine Sound Issues in Finland
   Carlo di Napoli, Pöyry Energy Oy, Finland (CN)
5. Wind Farms Noise - Brief Overview of Assessment and Prediction Methodology in the UK, Rob Shephard, UK, (RS)
6. Nord2000 for Wind Turbine Noise predictions,
   Bo Søndergaard, Delta Akustik, Denmark (BO)

7. Long range sound propagation over a sea surface,
   Ilkka Karasalo, FOI, Sweden (IK)
8. Using advanced noise propagation modeling programs in windfarm design,
   Dennis Siponen, VTT, Sweden (DS)
9. Wind farm noise measurements and residual noise estimation by modelling,
   Roberto Ziliani, ISMES, Italy (RZ)
10. Sound emission and sound propagation in forest terrain,
    Martin Almgren, ÅF-Ingemansson, Sweden (MA)
11. Sound propagation models and validation,
    Conny Larsson, Uppsala University, Sweden (CL)
12. Acoustic Noise Measurement,
    Prof. Arakawa, Univ. of Tokyo, Japan (PA)
13. Models of natural background noise and masking of wind turbine noise,
    Karl Bolin, Royal inst. of Technology, Sweden (KB)

DISCUSSION

Following the two days of presentations the floor was opened and a general discussion took place. A number of different topics were handled:

- Noise Country Limits
- Long Propagation noise on Offshore Installations
- Procedure for Immission Noise measurement.
- Measured data for validation of Sound Propagation Models
- Background Noise (Masking the noise)
- Future actions under the umbrella of IEA Wind

Bellow is a summary of the discussion:

Noise Country Limits

Different type of noise limits already exist in several countries. A general feeling is that already existing limits are conservative and protect neighbours of wind installations. In the on going IEA Task 28 "Social Acceptance of Wind Energy Projects", this issue will be elaborated further.

Long Propagation noise on Offshore Installations.

In Sweden there is an important concern about sound propagation from offshore wind installations. The results obtained using already existing propagation models gives high levels of noise even for wind farms located far away from the shore.

In Denmark, there are not complains about noise in the offshore installations.

The conclusion is that models are predicting higher noise level compared to real values. Work should be done to modify already existing models for noise propagation offshore.

Procedure for Immission Noise measurement

According with the information presented by the participants, the methodology to measure noise immission is not well defined.

CL stated that more measurements is required of meteorological data during the measurement campaigns, due to the fact that meteorological conditions have an strong influence in the results measured. It is well known that sound propagation in the atmosphere, is affected by temperature and wind speed gradients. Data required for validating the existing models, need to include extensive meteorological measured data.

The three most significant meteorological effects on sound propagation are: refraction, scattering by turbulence and atmospheric absorption. Meteorological effects were noticeable even at a distance of twenty five metres from the source and increased with decreasing receiver height. (CL).

SSz remarked the necessity of measure wind speed at hub height (near the WT) and at the same time the wind speed at 10 m high level near to the immission site. The wind speed measurement at hub height could be deduced form the WT power production.

The necessity to have guidelines to make noise immission measurements, in the vicinity of wind farms and wind turbine installations was identified.

The statistical treatment of measured data was discussed. More data than mean values of the complete distributions should be presented. In particular high levels should be presented as well as high sound variations.

The noise descriptors are different for the different propagation models. The noise descriptor should be unified trying to give the best information to protect neighbours of the WT noise.

Measured data for validation of Sound Propagation Models

Various propagation models have been developed to estimate the level of noise near residential areas. The availability of validated prognosis models generally accepted by the governmental and local authorities, will help planning new wind turbine installations.

It was expressed the need to have user friendly models public available, due to the fact that already existing models for sound propagation of noise from wind farms, are models usually existing at universities and research centres and not friendly to use (BO).

More measured data available are required to verify the existing sound propagation models. The validation of the models will allow reducing the time of required immission measurements, just needed for comparison with the predictions (RS).

SSz informed that measured data from the new Alpha Ventus Offshore Wind Farm could be available in the future to validate sea propagation models.

Background Noise

The existing noise environment at potential receiver locations (in the vicinity of a proposed wind farm site) must be properly determined for a representative range of conditions. This requires obtaining sufficient background noise measurements correlated with wind speed at the wind farm site.

It is not an easy task to determine background noise. In Holland standardised values for the background noise are used, while in France they measure the background noise level on the site.

One important question is what should be included in background noise. If it is not just natural sound then the background noise in an area will increase as more and more sound sources (industries, roads, other wind turbines etc) are introduced.

One issue of relevance for judging the effect of a certain immission from wind turbines is the possibility to estimate masking from background noise. In some experiences the high background level noise masks the high level noise produced by the wind turbines, eliminating the problem.

Future actions under the umbrella of IEA Wind

Several options were discussed:

- New Topical Expert Meeting on this subject
- Elaboration of Recommended Practices for Noise Immission Measurement
- New Task on this subject

The participants decided that an additional meeting would be required on the noise immission issue within two years.

BO, convenor of the IEC 61400-11 WG, informed that for the time being there is no specific work inside the IEC to develop standards for noise immission measurement in wind farms. In general the IEC WG produce standards from already existing knowledge, but for immission measurements there is still a need to develop new knowledge, which presently is outside the scope of IEC WG. On the other hand the average time required to produce an IEC standard is 2/3 years.

The participants agreed to elaborate a Recommended Practices document for “Noise Measurement Immission”. And Ad-hoc group will be created. Several of the participants expressed their interest to be included in the Ad-hoc group (their main problem is how to finance their participation).

The measurement of the low frequency noise indoors should be included in the scope of the future Recommended Practices.

List of participants

IEA RD&D Wind Task 11, Topical Expert Meeting
Sound Propagation Model and Validation
Stockholm
5-6 May, 2009

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Not in picture
Ilkka Karasalo