# The inaudible noise of wind turbines


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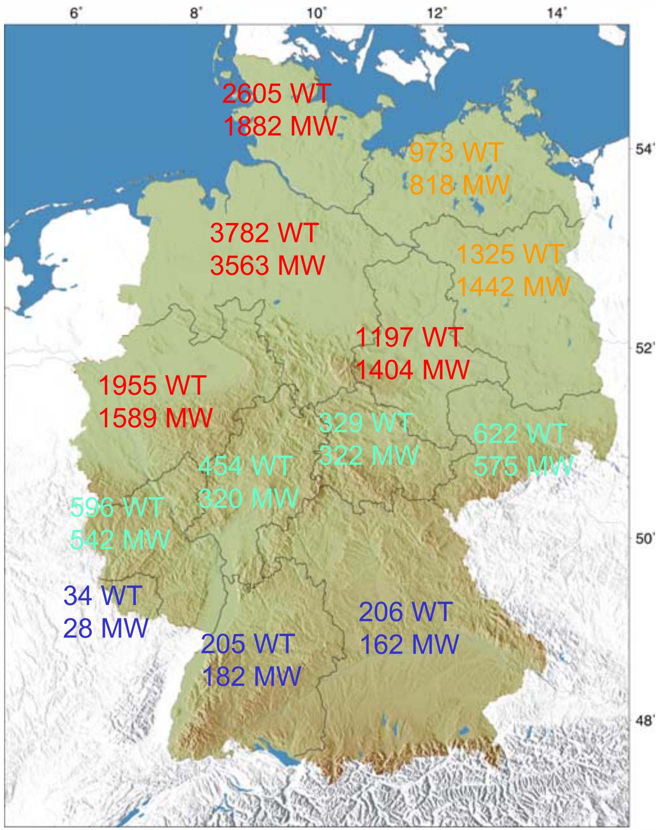
# Regional distribution of wind turbines in Germany

source: Ender, 2003




| | |
|---|---|
| Baden-Würtemberg | 0.6 |
| Bayern | 0.3 |
| Saarland | 1.1 |
| Hessen | 2.1 |
| Rheinland-Pfalz | 3.0 |
| Sachsen | 3.4 |
| Thürigen | 2.2 |
| Brandenburg | 4.5 |
| Mecklenburg-Vorpommern | 4.1 |
| Niedersachsen | 8.0 |
| Nordrhein-Westfalen | 5.9 |
| Sachsen-Anhalt | 5.8 |
| Schleswig-Holstein | 16.6 |

# wind turbines / 100 km$^2$

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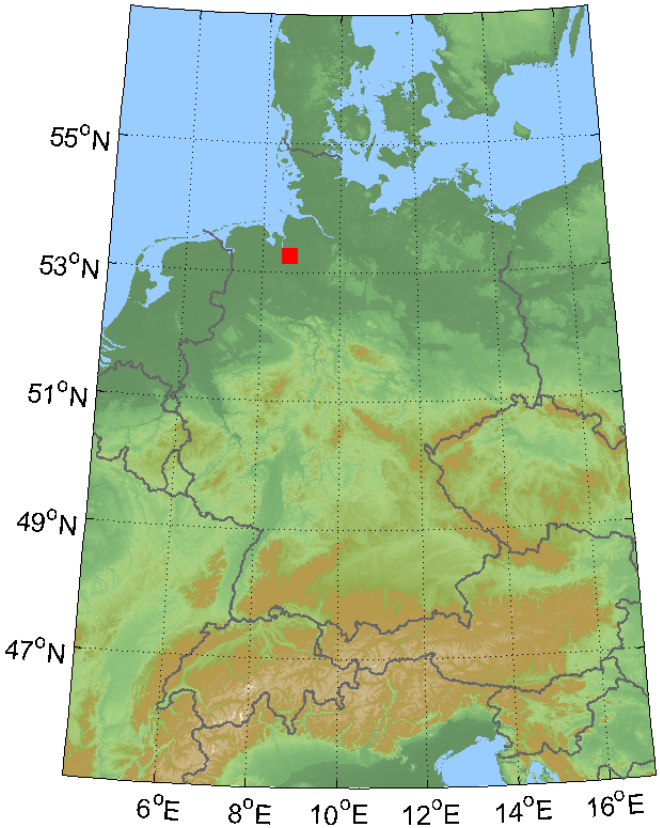
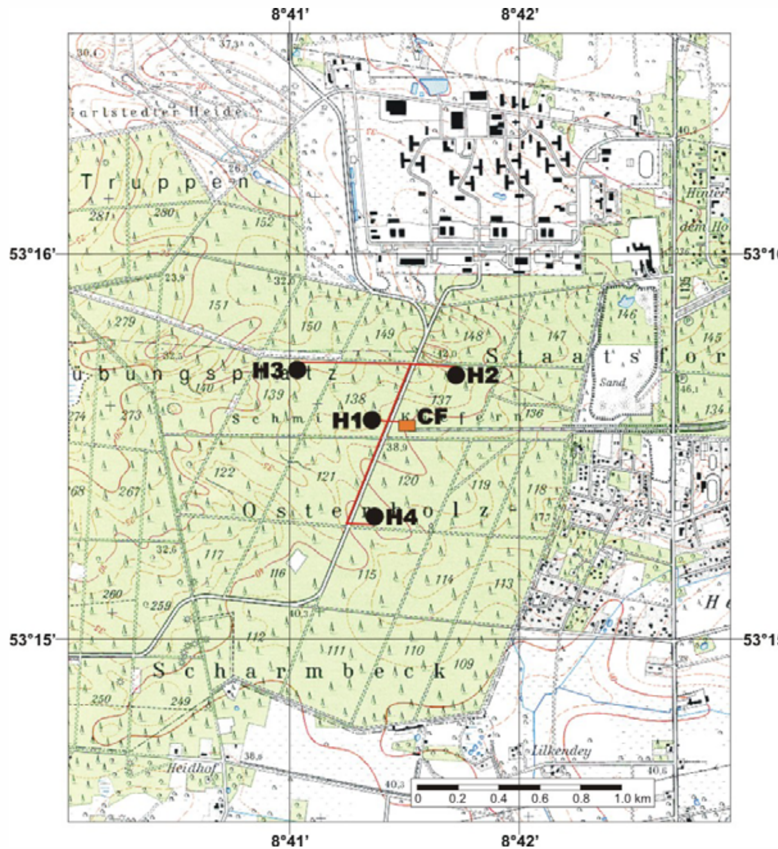
# The German infrasound station IGADE

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# Milestones of the establishment of IGADE

Site Inspection

30 April 2003

Installation of IGAH1

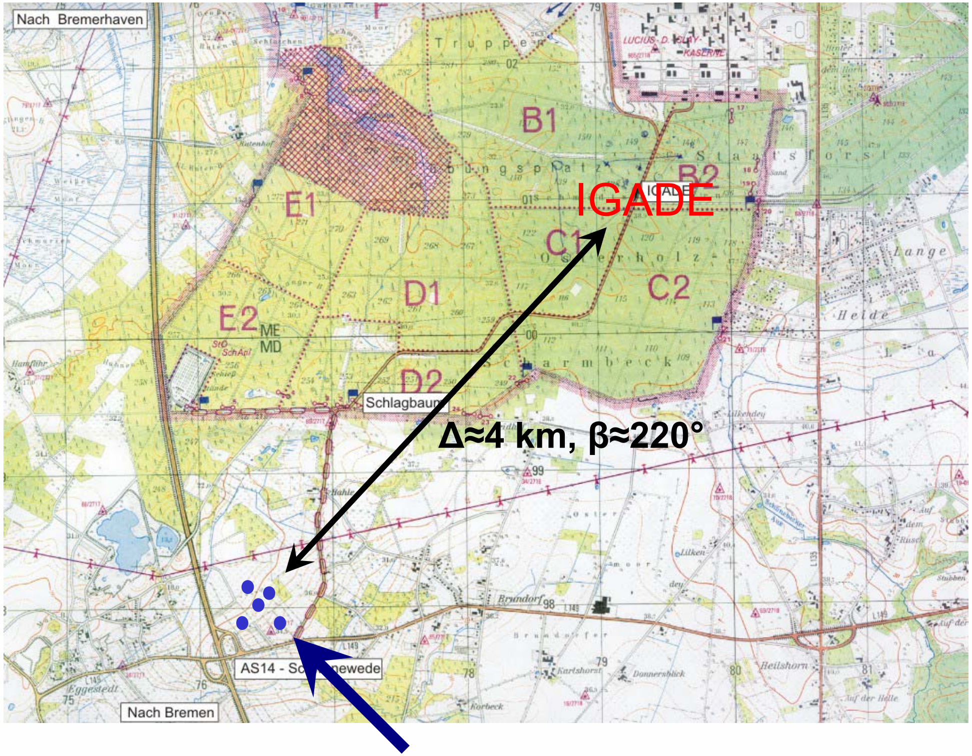
September / October 2003

Extension to
4 element array

September 2004 - January 2005

Growing number of Wind turbines close to the array

April / May 2005

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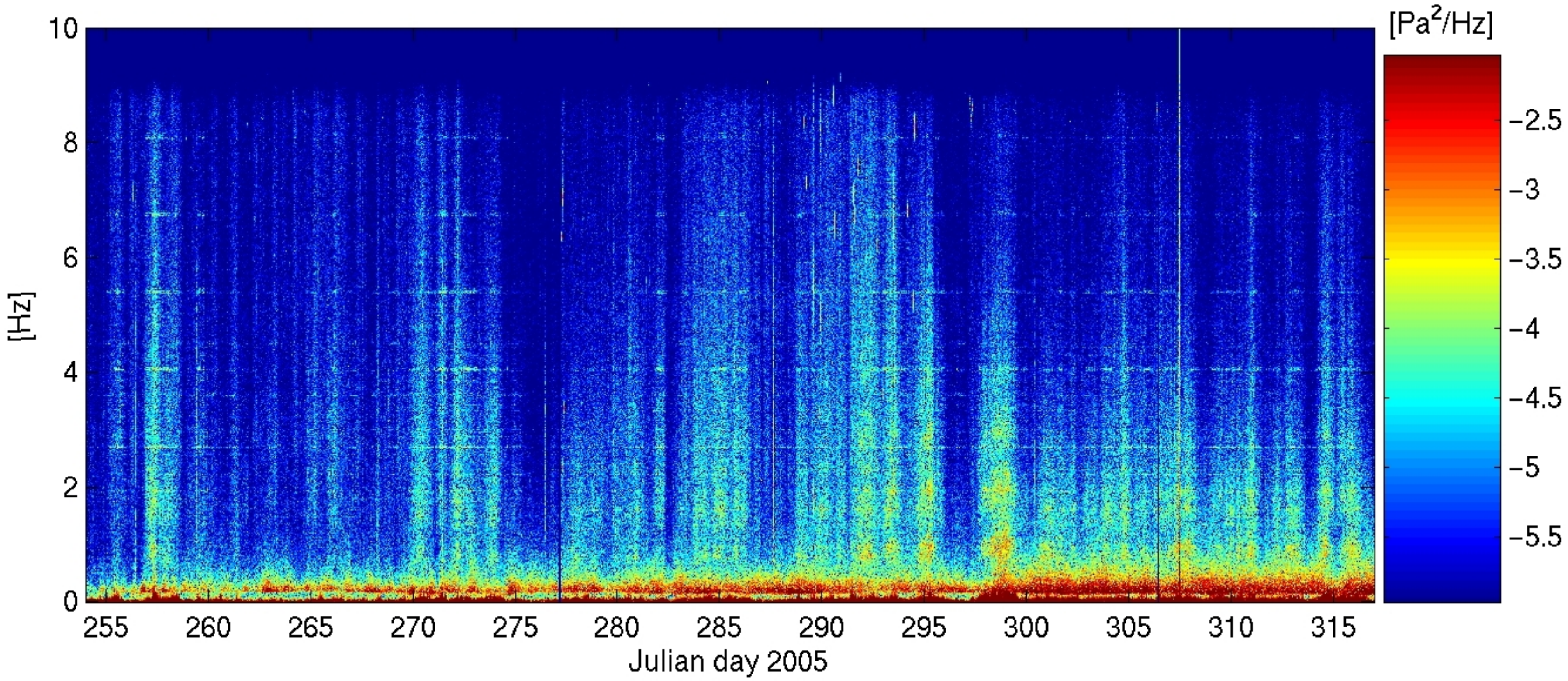
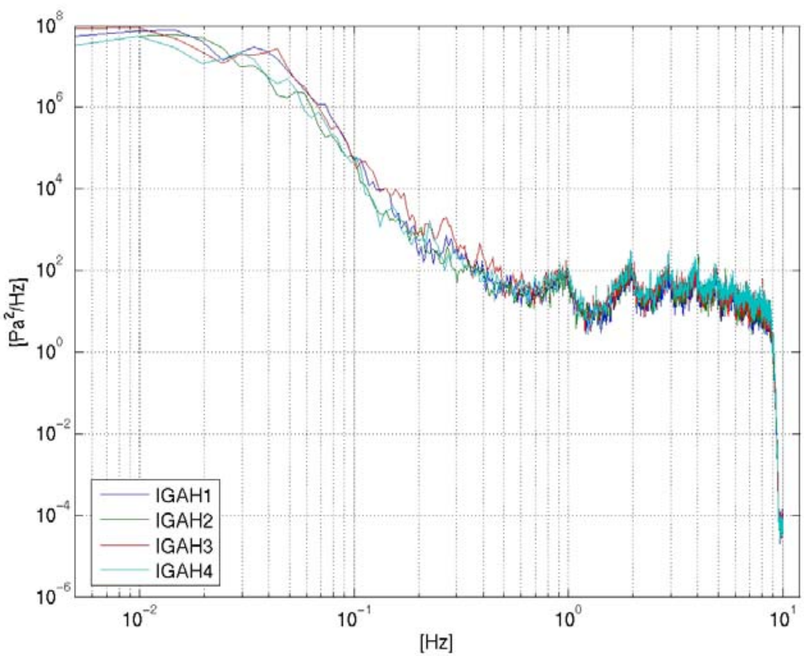
# The spectral fingerprint of wind turbines: IGAH1



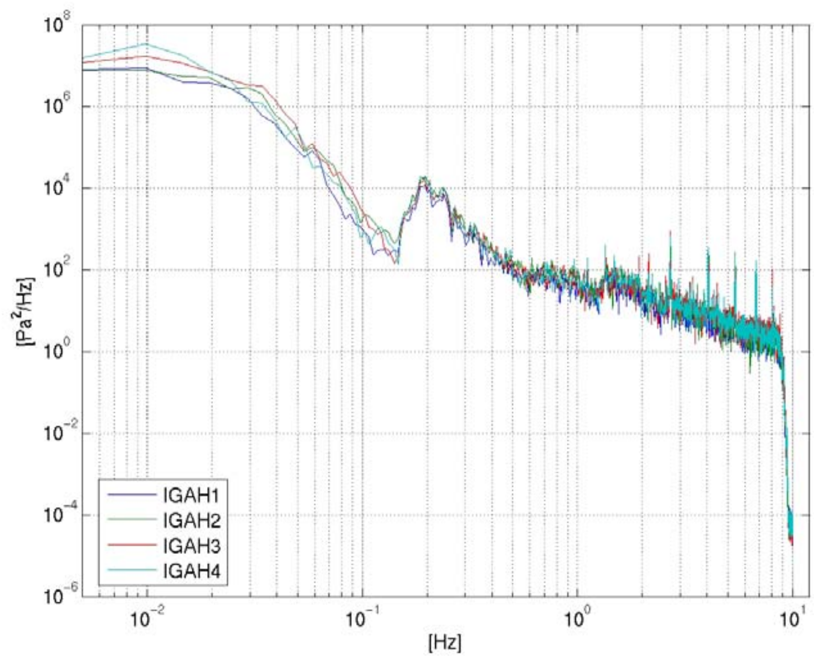
# The spectral fingerprint of wind turbines: IGADE

07-May-2005 12:10 – 12:30 (UTC)




3 blades, Δf=1 Hz, 20 rpm

14-Sep-2005 19:40 – 20:00 (UTC)




3 blades, Δf=1.35 Hz, 27 rpm

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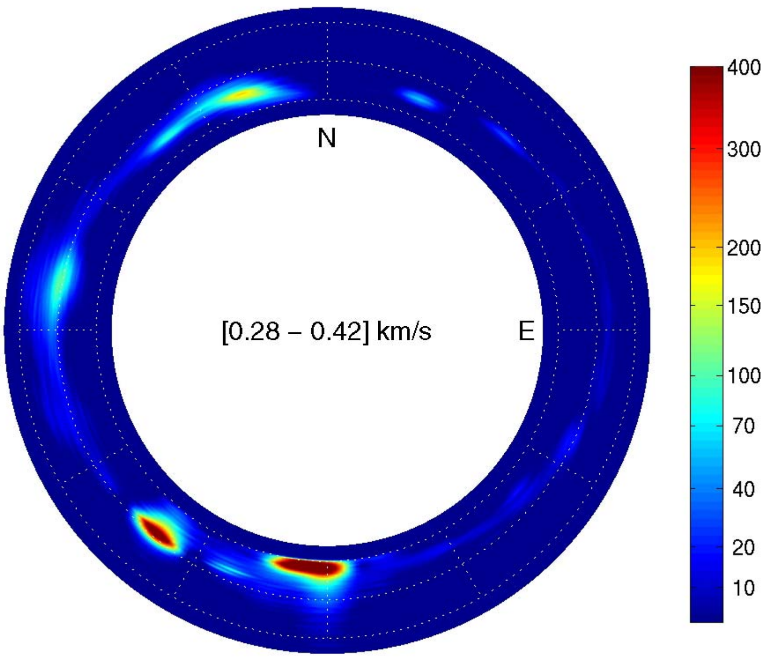
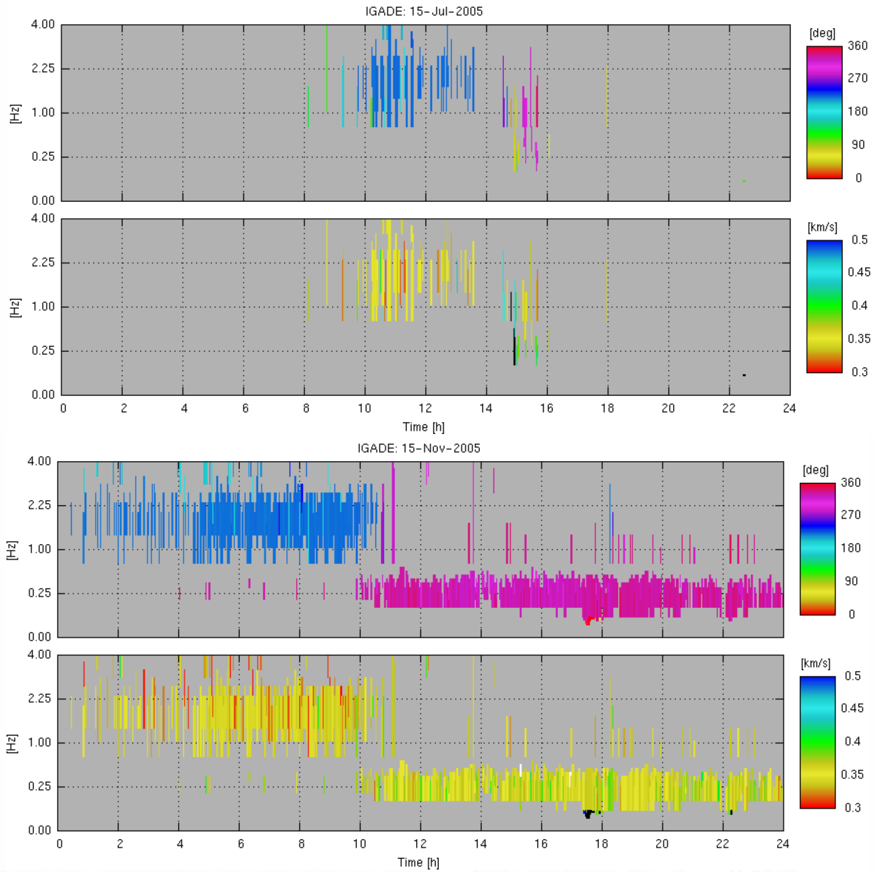
# The fingerprint of wind turbines in the routine analysis

PMCC analysis




February – November 2005, [0.7 4.0] Hz

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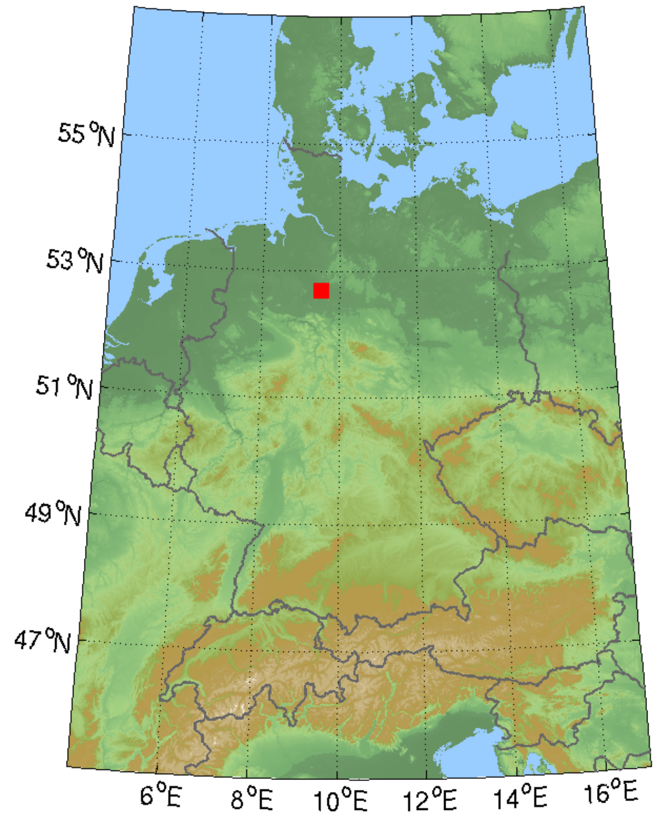
# A single wind turbine in northern Germany

VESTAS V47
200 kW
h=65 m, r=24 m
rpm=[20 26]

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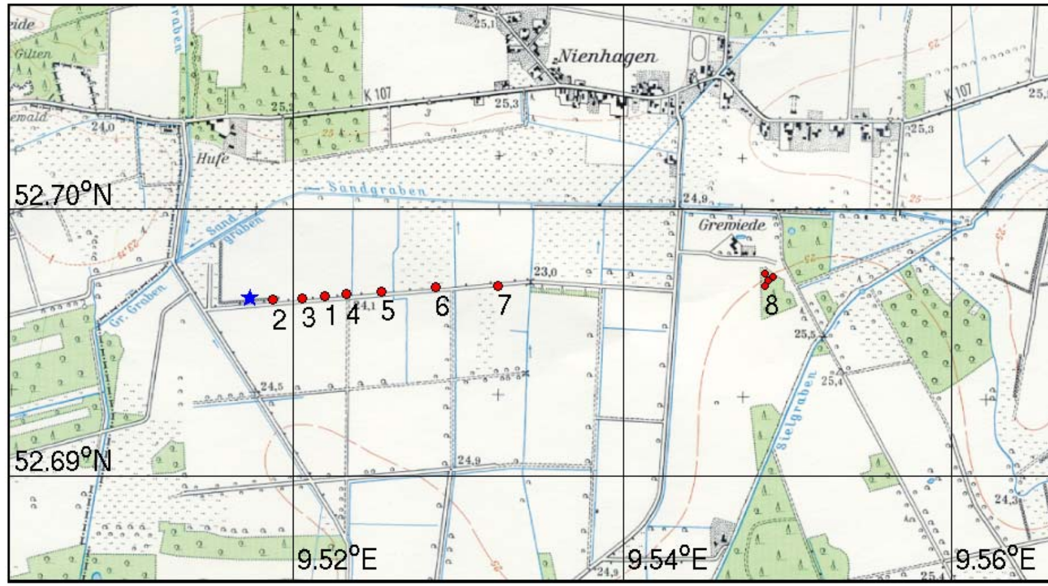
# Configuration of the Hufe field experiment




1 2 3 4: 07-Jul-2004 - 19-Jul-2004, HUF01, HUF02, HUF03, HUF04
1 5 6 7: 19-Jul-2004 - 29-Jul-2004, HUF01, HUF05, HUF06, HUF07
8 : 29-Jul-2004 - 05-Aug-2004, HUF08, HUF09, HUF10, HUF11

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# Measuring along the track and in the wood

Huf07

Huf06

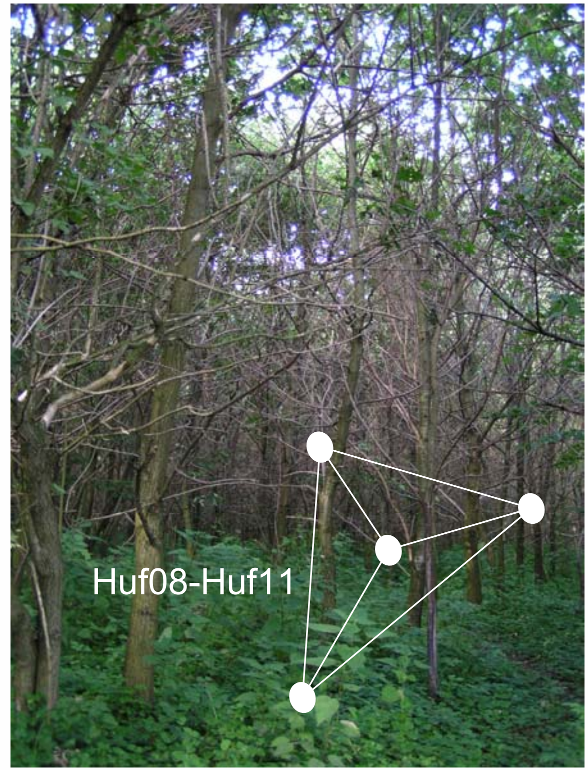
Huf05

Huf04

Huf03

Huf02

Huf01

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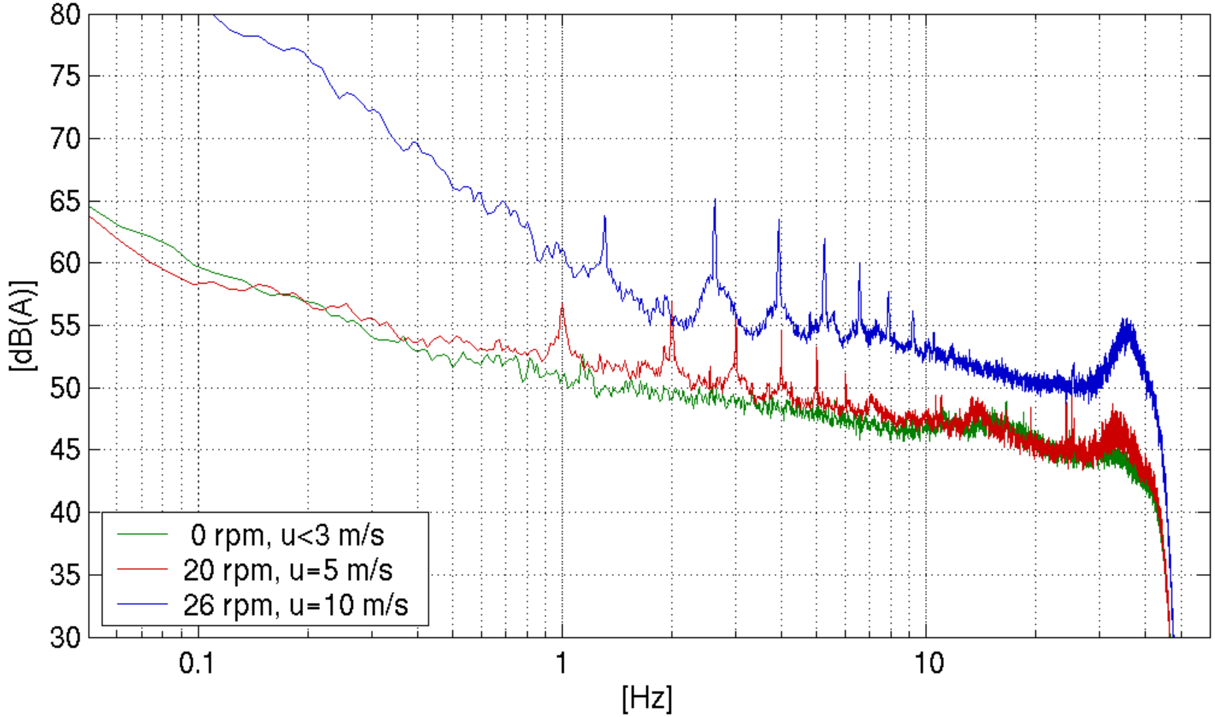
# Station Huf01

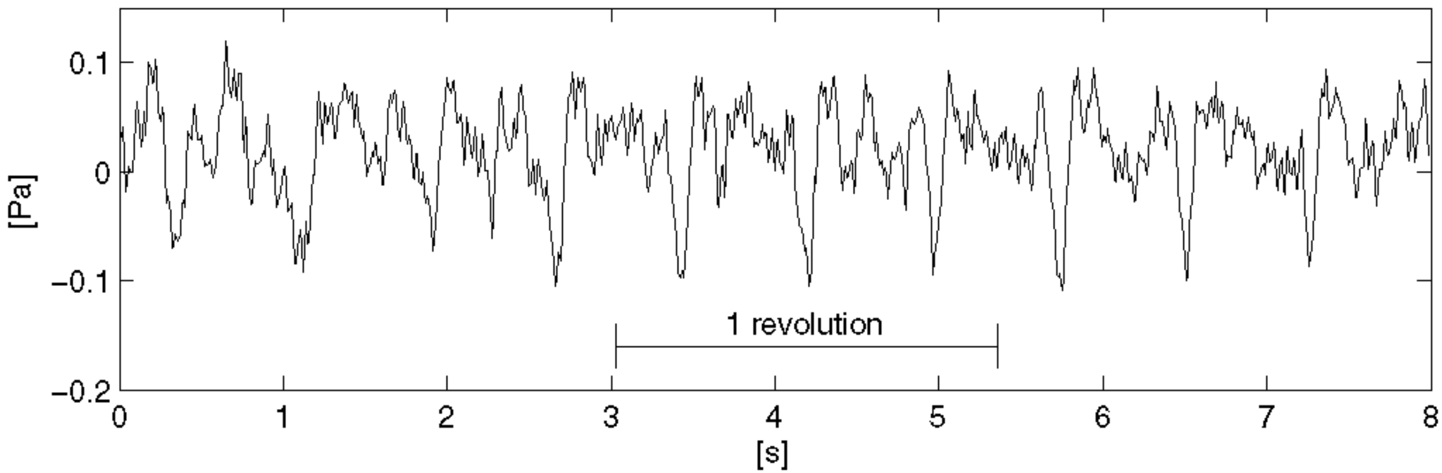
# Measured signals, Huf03, d=200 m

frequency domain



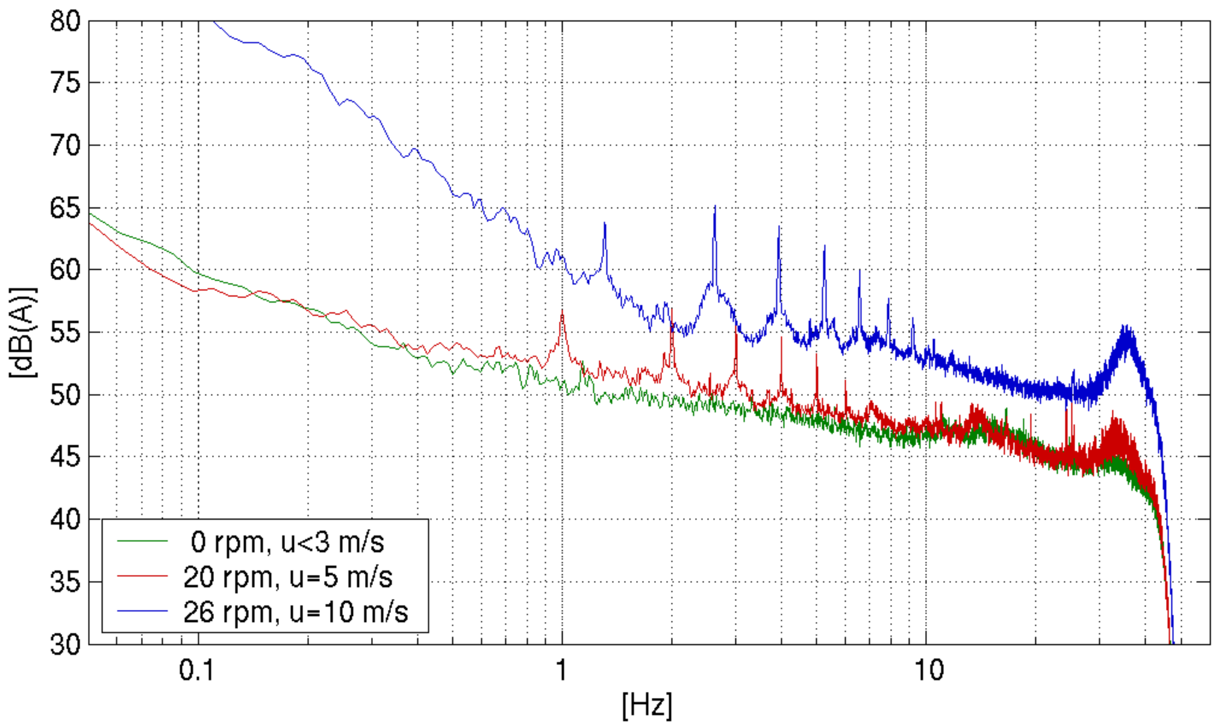
# Measured signals, Huf03, d=200 m

time domain, 0.5 Hz high pass filtered

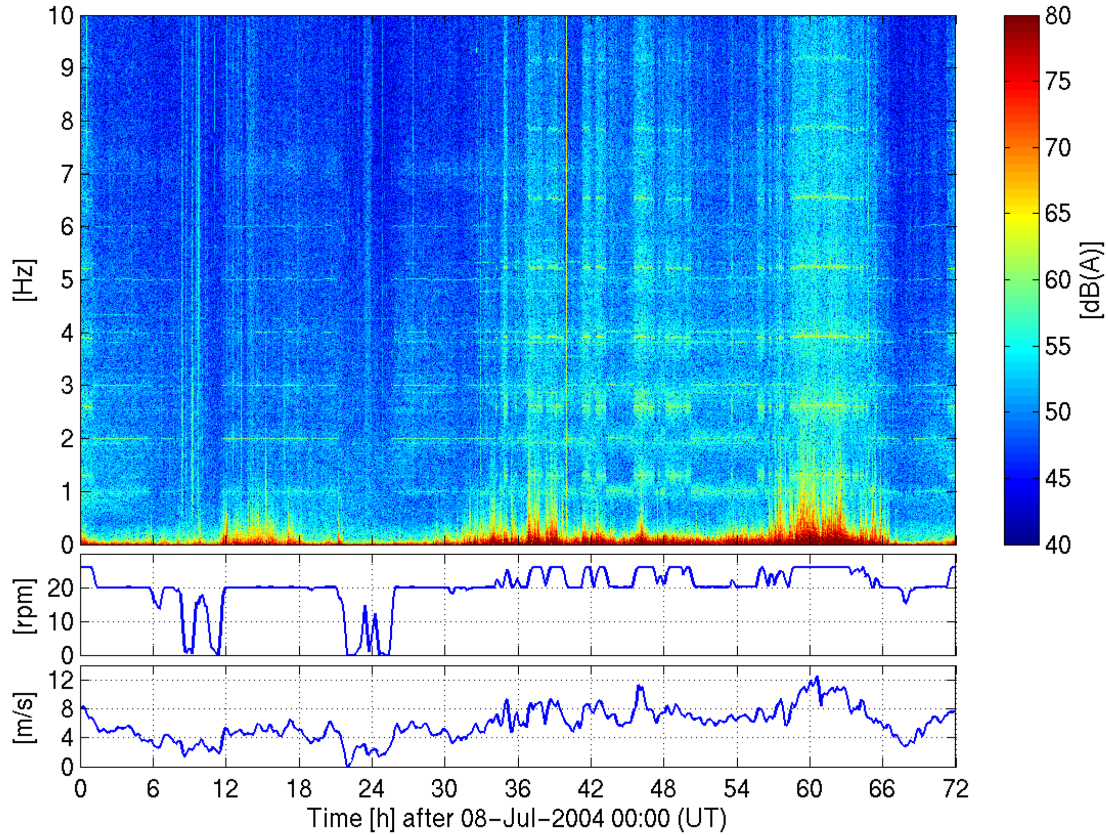


# Measured signals, Huf03, d=200 m

frequency domain



# Time-frequency analysis, Huf03, d=200 m

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# Theoretical SPL-estimation

Hubbard & Shepherd (1991, JASA)

$$P_n = \frac{k_n\sqrt{2}}{4\pi d}\sum_m \left(e^{im(\theta-\pi/2)} J_x(k_n R_e \sin\gamma)\right)\cdot\left(a_m^T \cos\gamma - \frac{nB-m}{k_n R_e} a_m^Q\right)$$

$P_n$ – RMS sound pressure of the n-th harmonic
n – sound pressure harmonic number
$k_n$ – nBω/c
B – number of blades
ω – rotor speed
$c_0$ – sound speed
$R_e$ – effective blade radius

d – distance from the rotor
m – blade loading harmonic index (m=…,-1,0,1,..)
$J_x$ – Bessel function of first kind and of order x=nB-m
γ – azimuth to listener
θ – altitude angle to listener
$a_m^Q$ – complex Fourier coefficients of thrust forces
$a_m^T$ – complex Fourier coefficients of torque forces

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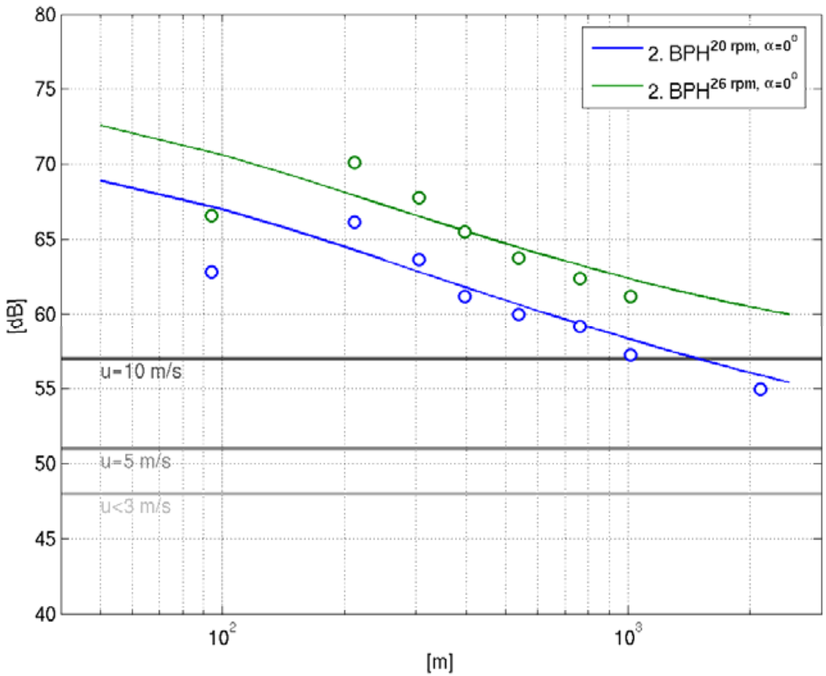
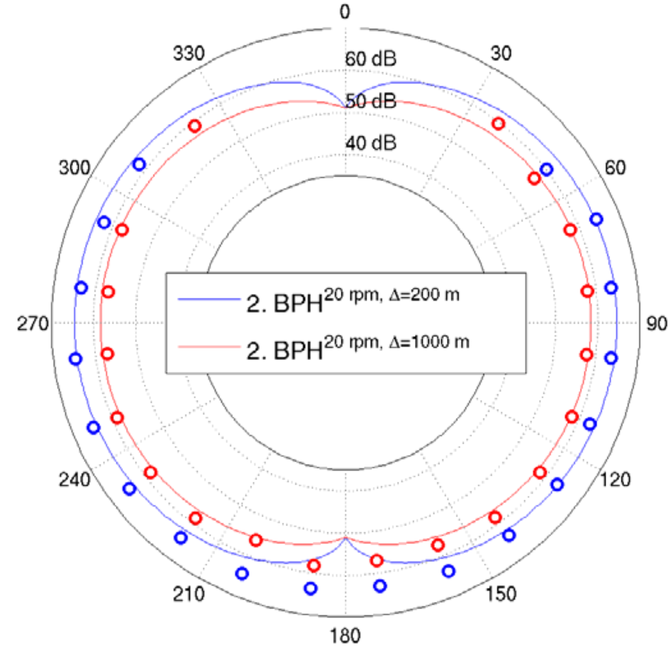
# Comparison between measured and estimated SPL

SPL as a function of distance




SPL as a function of azimuth




account for surface effects (e.g. reflections) by adding 3 dB to the estimated curves

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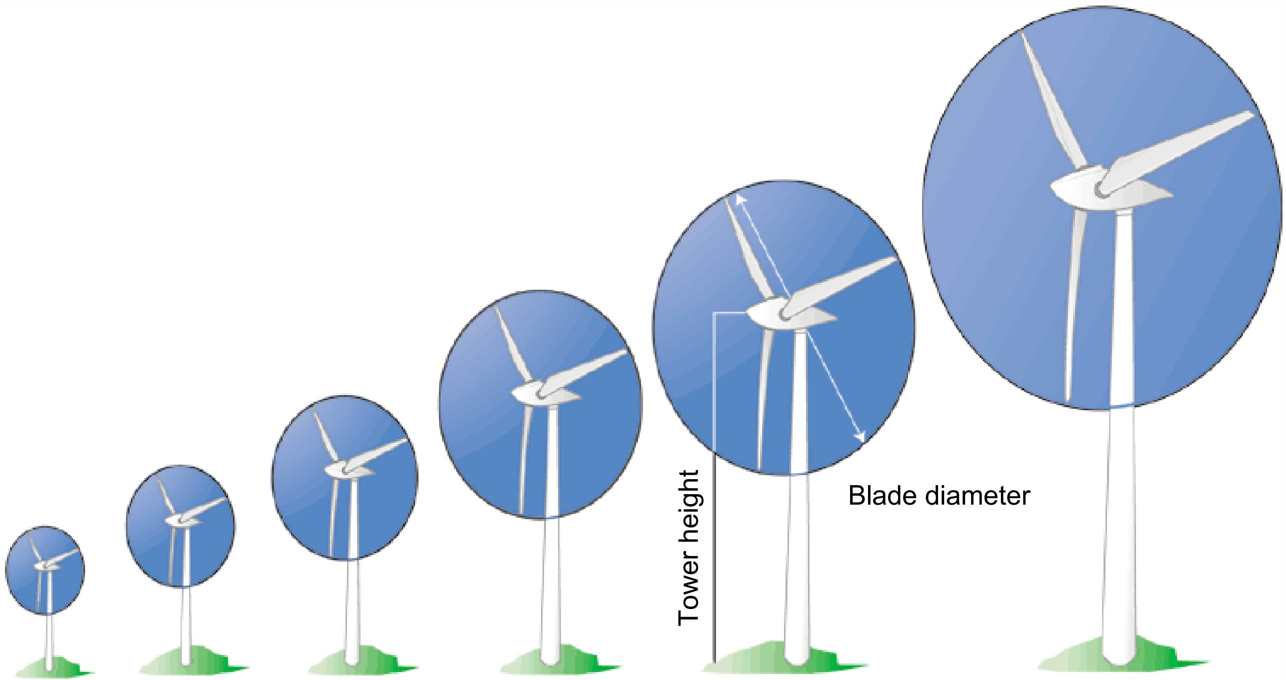
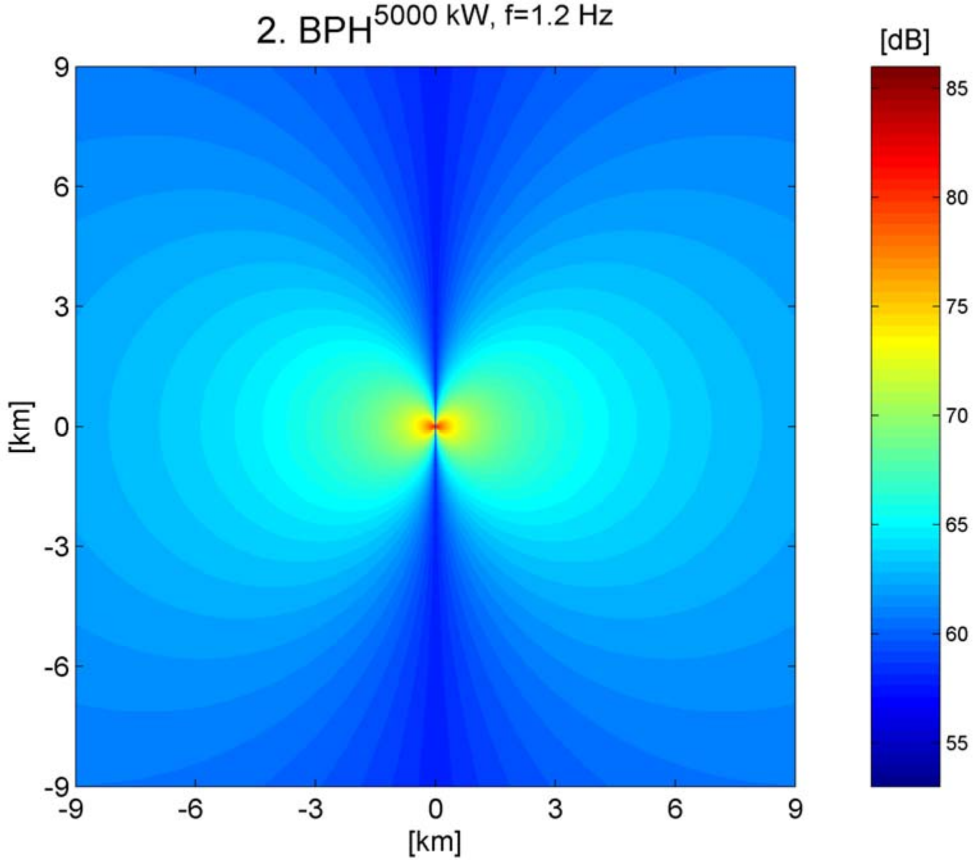
# Estimating the SPL generated by wind turbines




| | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 |
|---|---|---|---|---|---|---|
| **Power** | : 30 kW | 80 kW | 250 kW | 600 kW | 1.500 kW | 5.000 kW |
| **Blade diameter** | : 15 m | 20 m | 30 m | 46 m | 70 m | 115 m |
| **Tower height** | : 30 m | 40 m | 50 m | 78 m | 100 m | 120 m |
| **Energy production per year** | : 35.000 kWh | 95.000 kWh | 400.000 kWh | 1.250.000 kWh | 3.500.000 kWh | ca. 17.000.000 kWh |

# Estimating the SPL generated by (a) large wind turbine(s)

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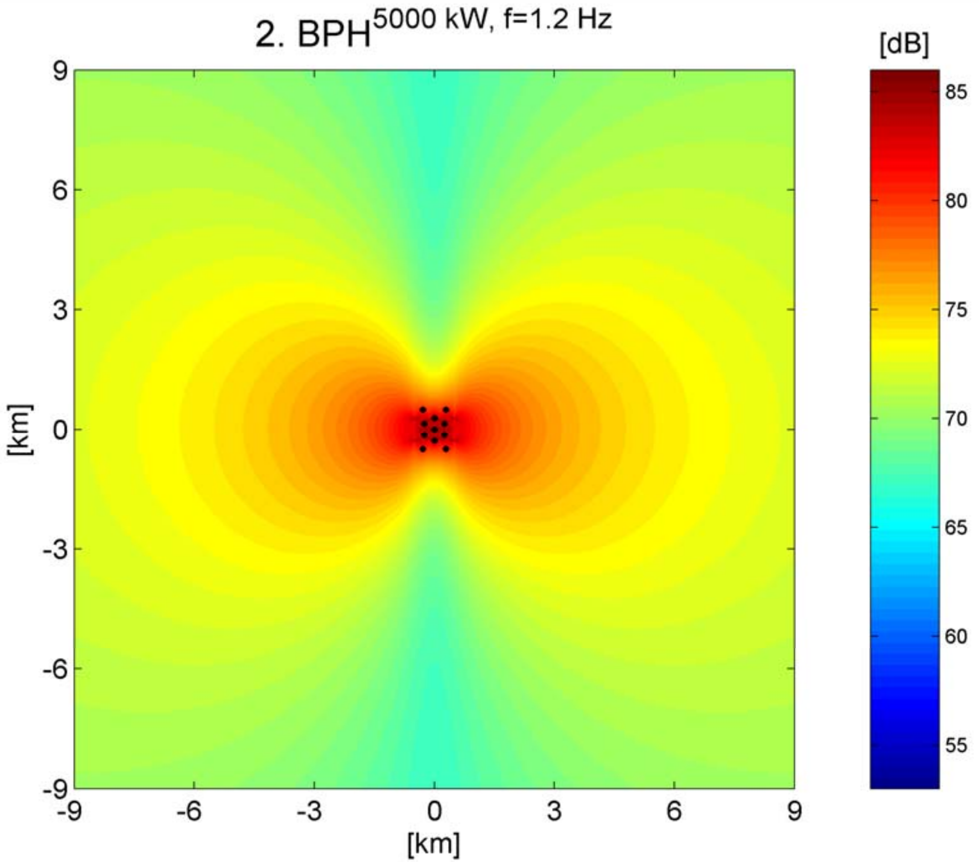


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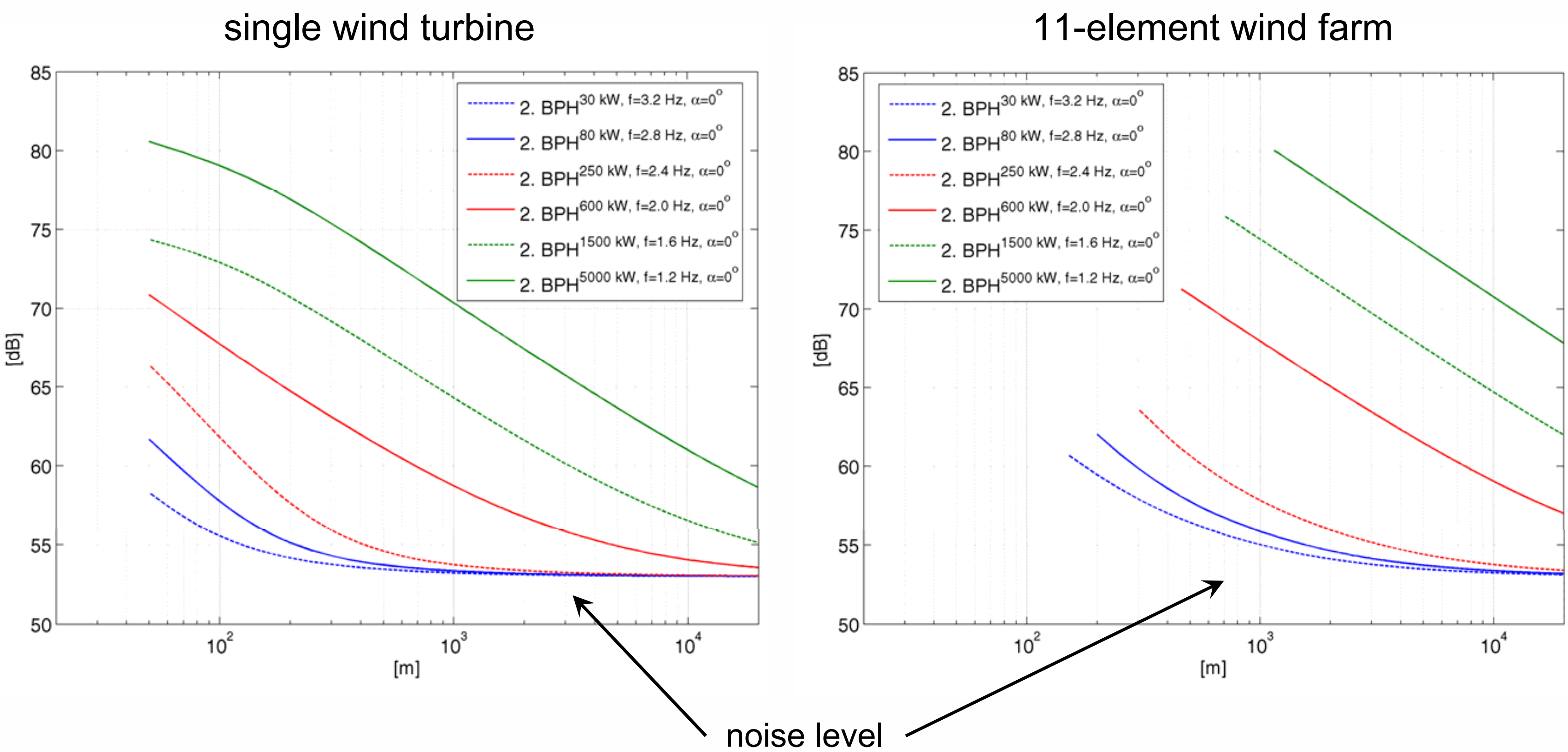
# Estimating the SPL generated by Wind Turbines/Farms at ~2 Hz



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# Conclusions

- number of wind turbines and their size is constantly growing

- wind turbines and wind farms generate strong infrasonic noise which is characterized by their blade passing harmonics (monochromatic signals)

- generated noise of wind turbines can theoretically be estimated
  - geometrical spreading ~ $R^{-1}$
  - SPL ~ $rpm^4$

- recordings from field measurements near a single wind turbine show that the theoretical model is also valid for frequencies below a few Hz

- minimum distance between an infrasound array and a wind farm can be estimated to avoid reduction of the array's detection capability (e.g. 600MW wind turbine: d>15 km, 11-element wind farm: d>30 km)

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