

The inaudible noise of wind turbines



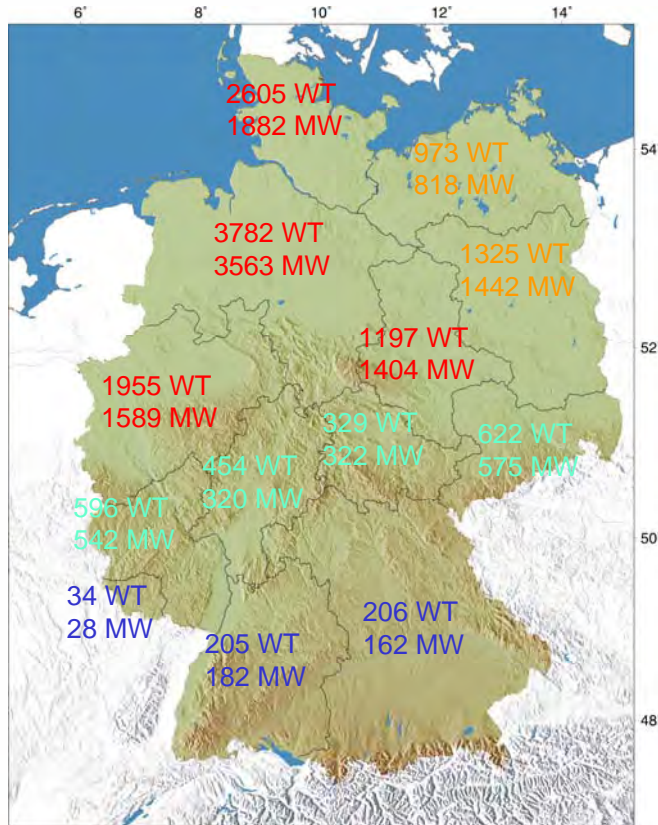
Lars Ceranna, Gernot Hartmann,
and Manfred Henger

Presented at the Infrasound Workshop
November 28 – December 02, 2005, Tahiti

Federal Institute for Geosciences and Natural Resources
(BGR), Section B3.11
Stilleweg 2, 30655 Hannover, Germany

Regional distribution of wind turbines in Germany

source: Ender, 2003



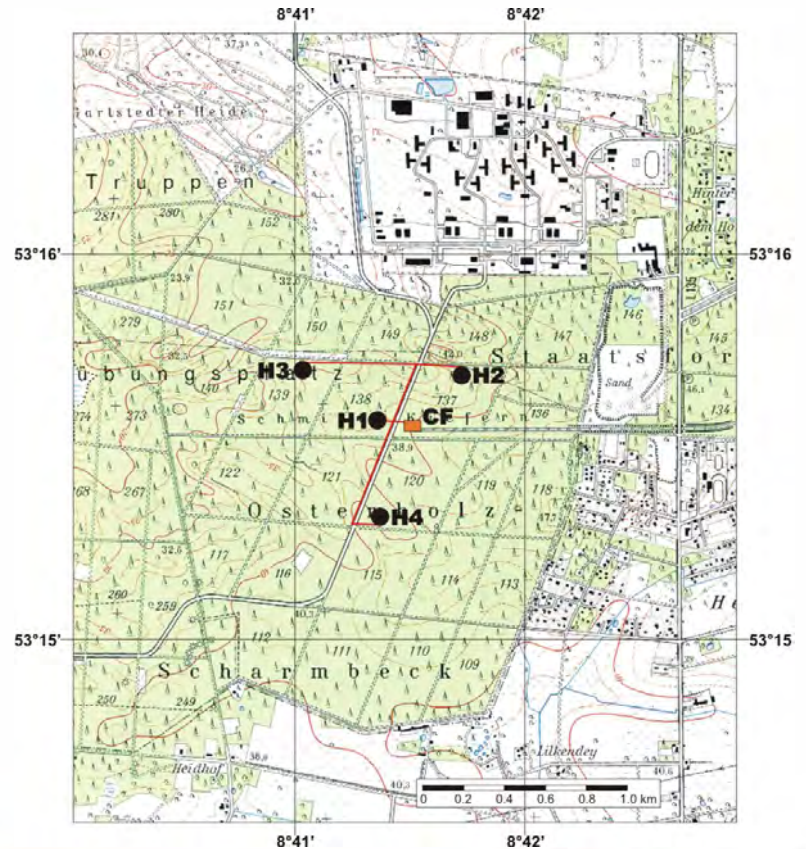
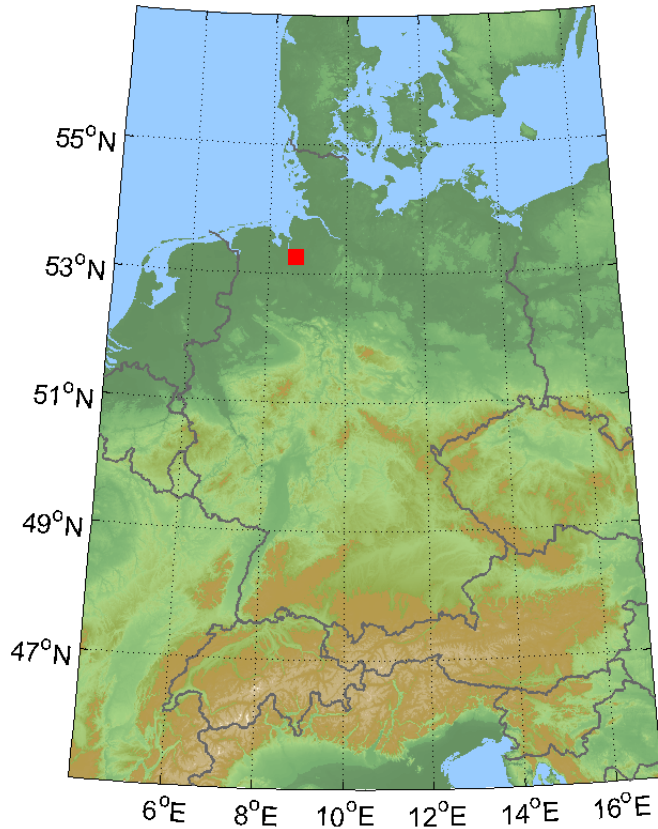
Baden-Württemberg	0.6
Bayern	0.3
Saarland	1.1
Hessen	2.1
Rheinland-Pfalz	3.0
Sachsen	3.4
Thüringen	2.2
Brandenburg	4.5
Mecklenburg-Vorpommern	4.1
Niedersachsen	8.0
Nordrhein-Westfalen	5.9
Sachsen-Anhalt	5.8
Schleswig-Holstein	16.6

wind turbines / 100 km²

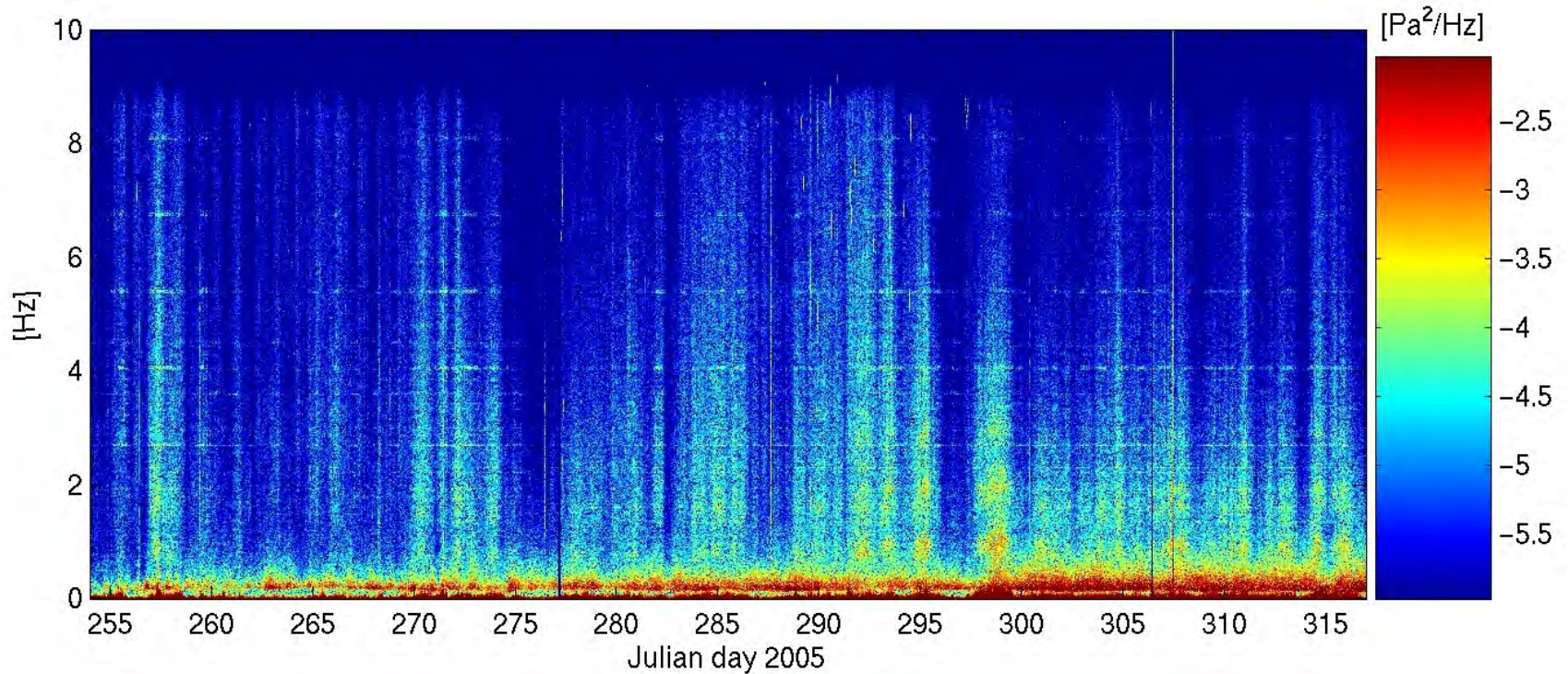
Content

- The Influence of Wind turbines on Infrasound recordings: IGADE
 - The German Infrasound Station IGADE
 - Data Examples, routine Analysis
- Noise Measurements at a single Wind Turbine
- Theoretical Estimation of the Sound Pressure Level
 - Comparison with Measurements
 - Scenarios, large Wind Farms, 5 MW Wind Turbines
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The German infrasound station IGADe

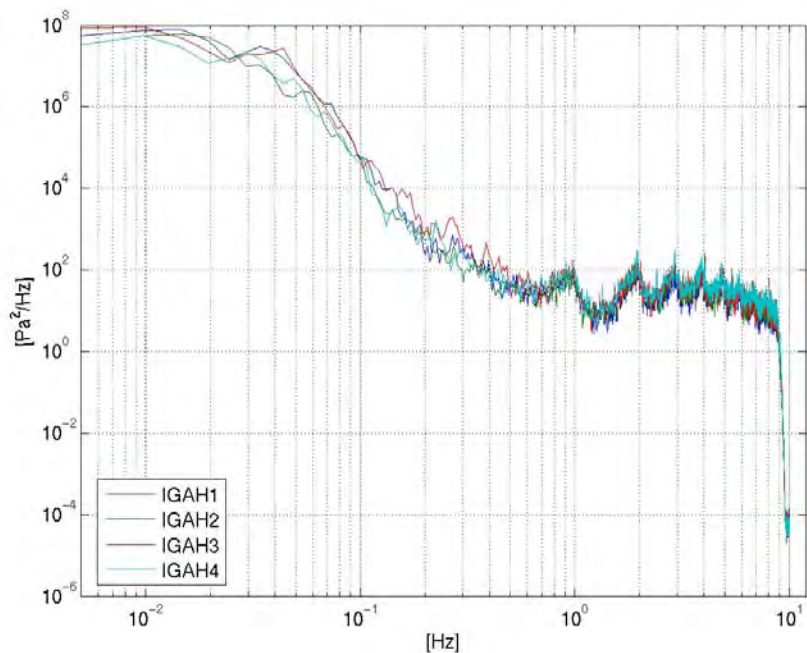


The spectral fingerprint of wind turbines: IGAH1



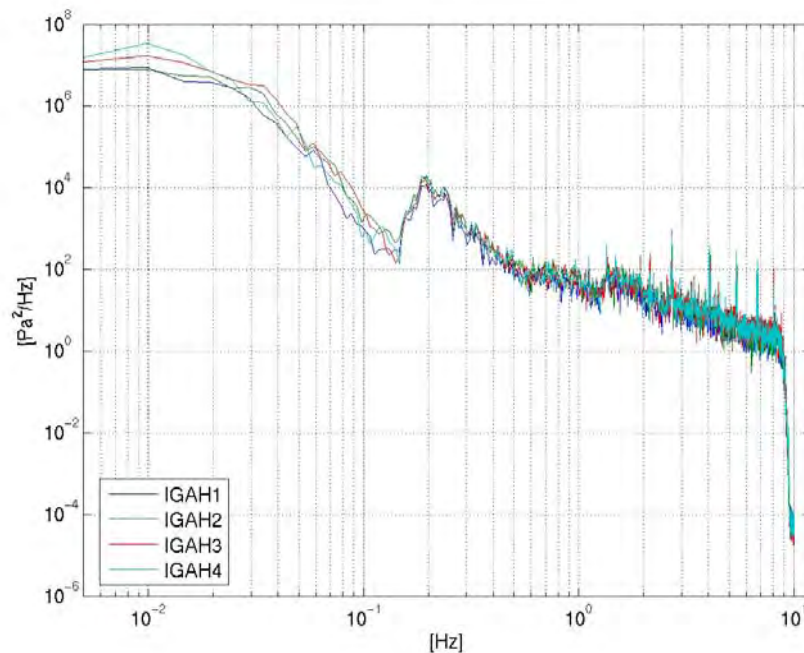
The spectral fingerprint of wind turbines: IGADe

07-May-2005 12:10 – 12:30 (UTC)



3 blades, $\Delta f=1$ Hz, 20 rpm

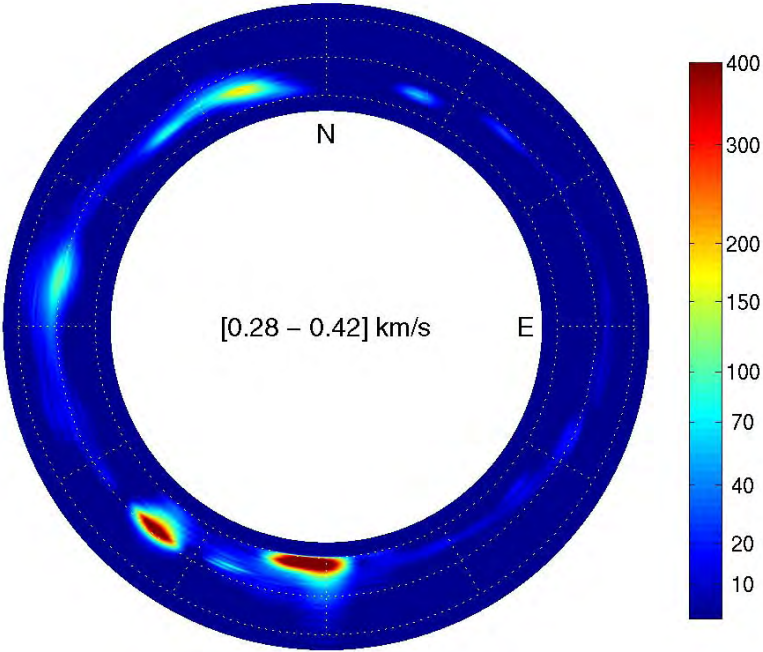
14-Sep-2005 19:40 – 20:00 (UTC)



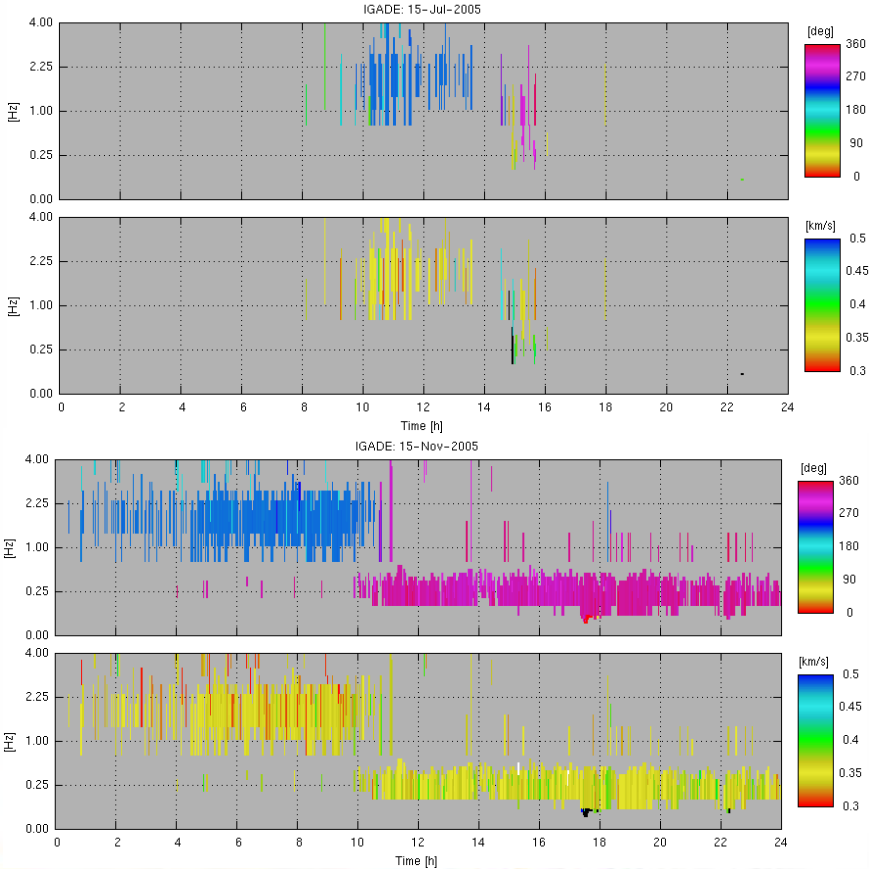
3 blades, $\Delta f=1.35$ Hz, 27 rpm

The fingerprint of wind turbines in the routine analysis

PMCC analysis



February – November 2005, [0.7 4.0] Hz



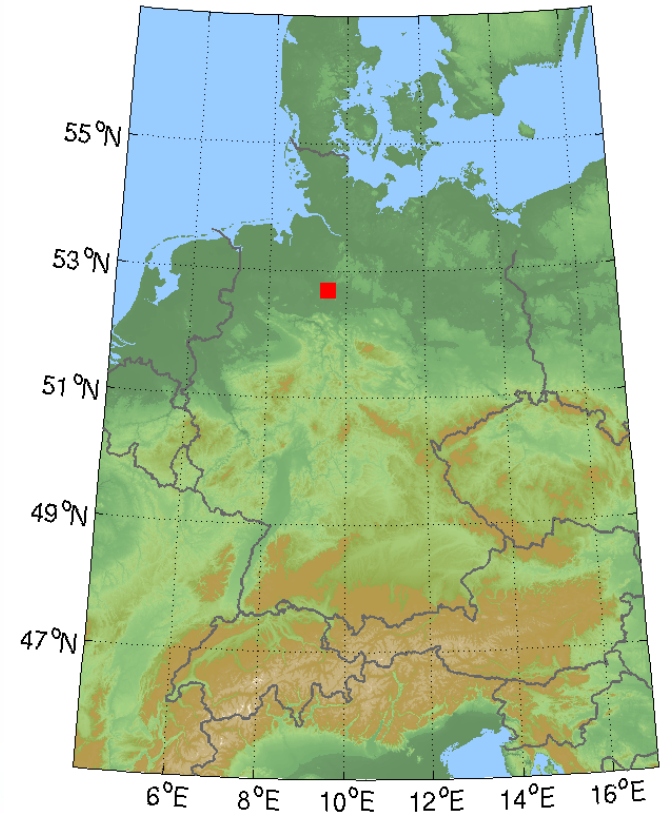
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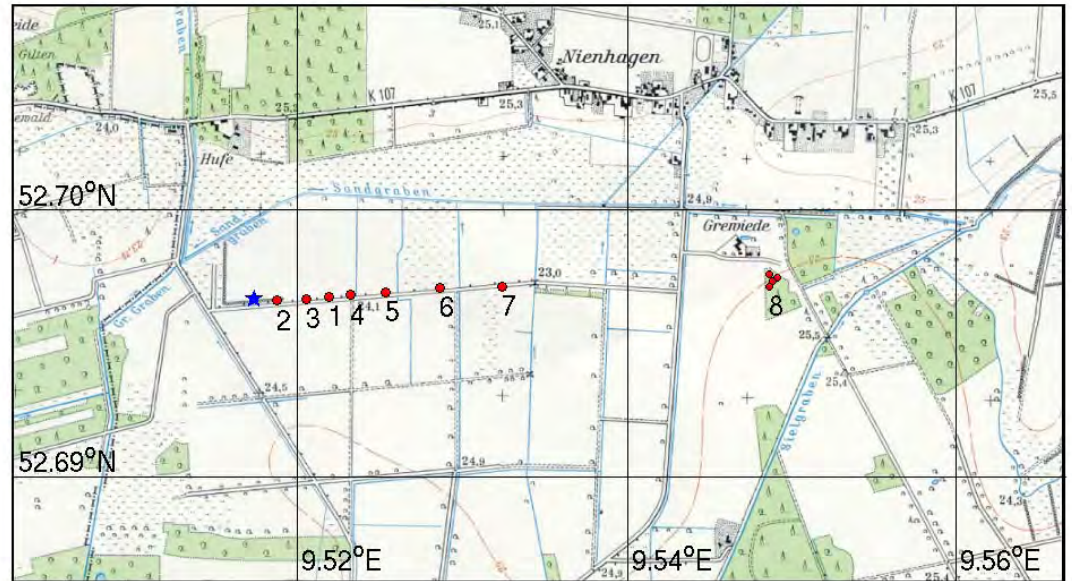
A single wind turbine in northern Germany



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



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

Measuring along the track and in the wood



Huf07

Huf06

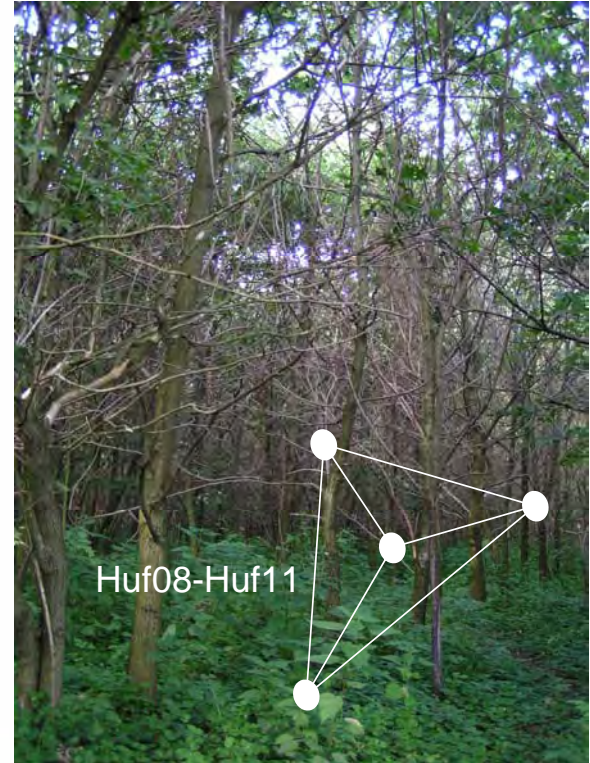
Huf05

Huf04

Huf03

Huf02

Huf01

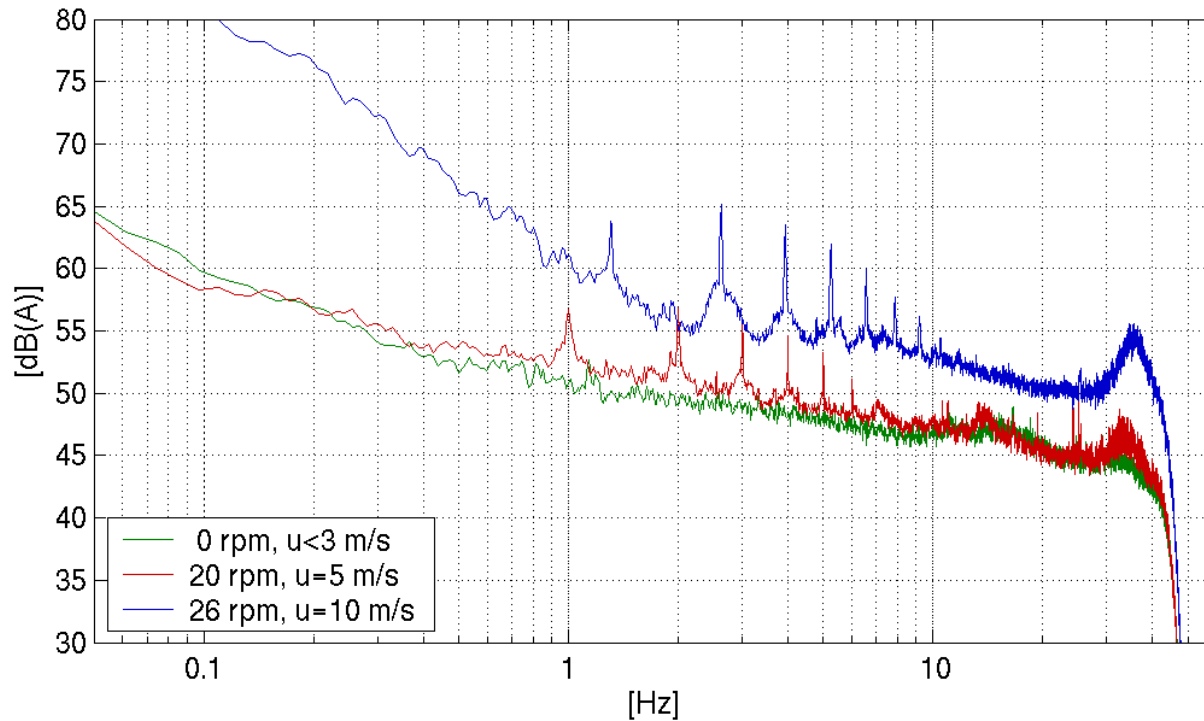


Station Huf01



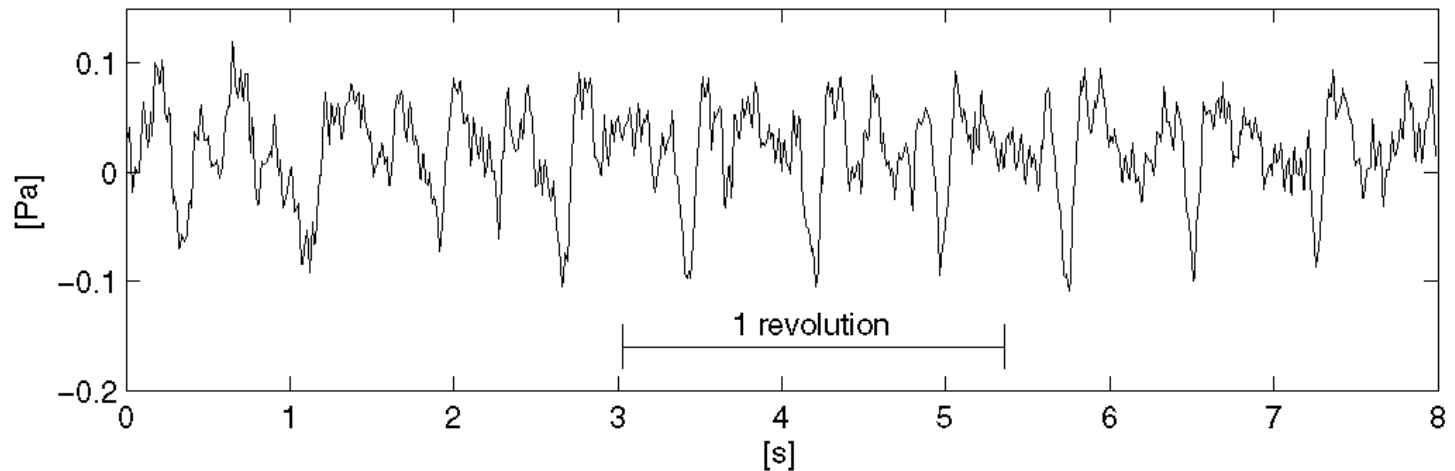
Measured signals, Huf03, d=200 m

frequency domain



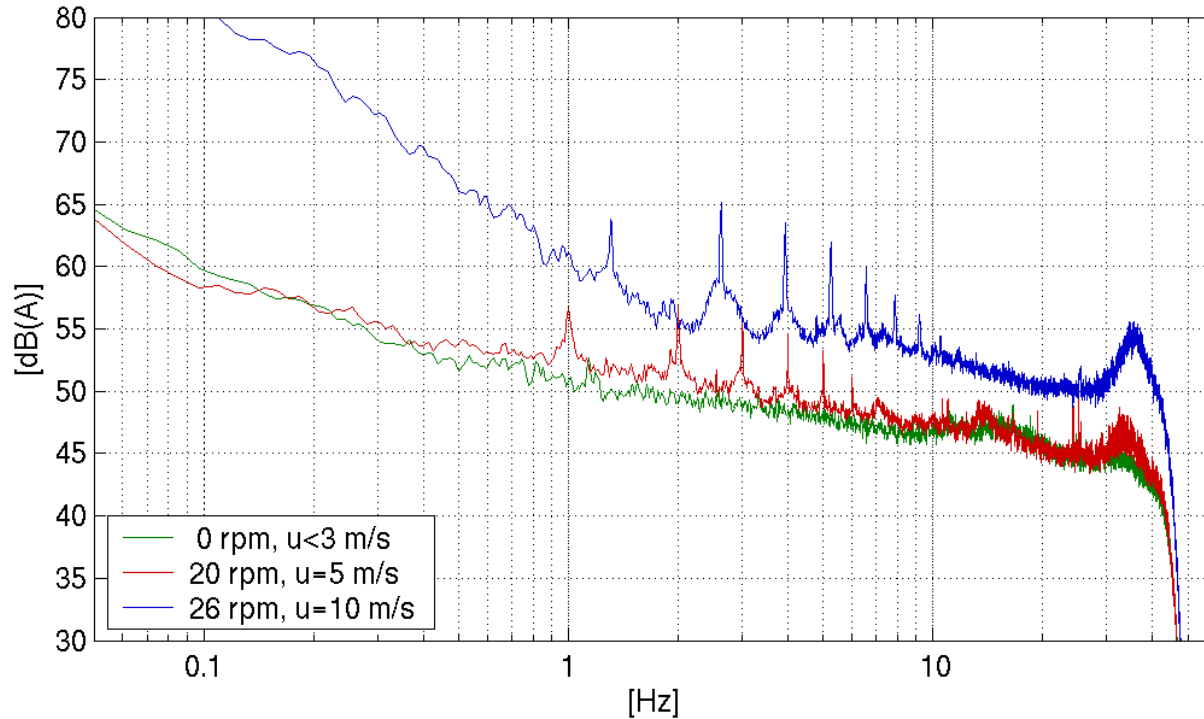
Measured signals, Huf03, d=200 m

time domain, 0.5 Hz high pass filtered

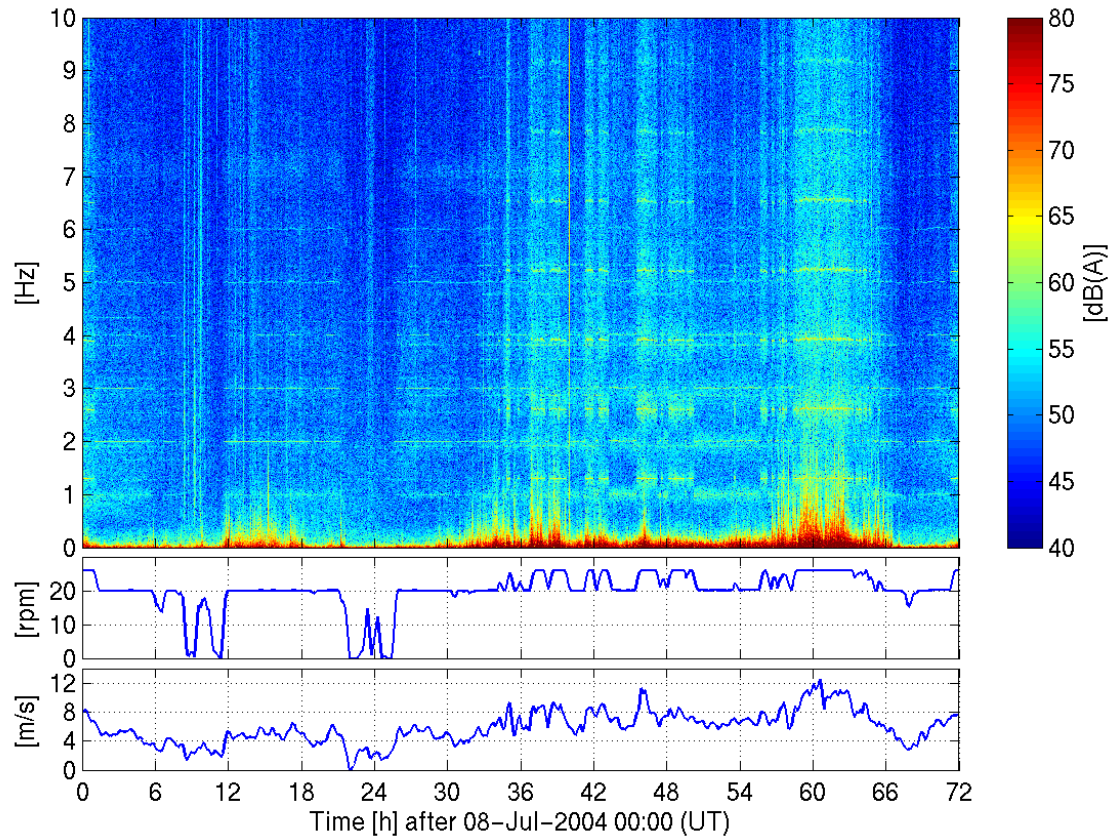


Measured signals, Huf03, d=200 m

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 – $nB\omega/c$

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 ($m = \dots, -1, 0, 1, \dots$)

J_x – Bessel function of first kind and of order $x = nB - m$

γ – azimuth to listener

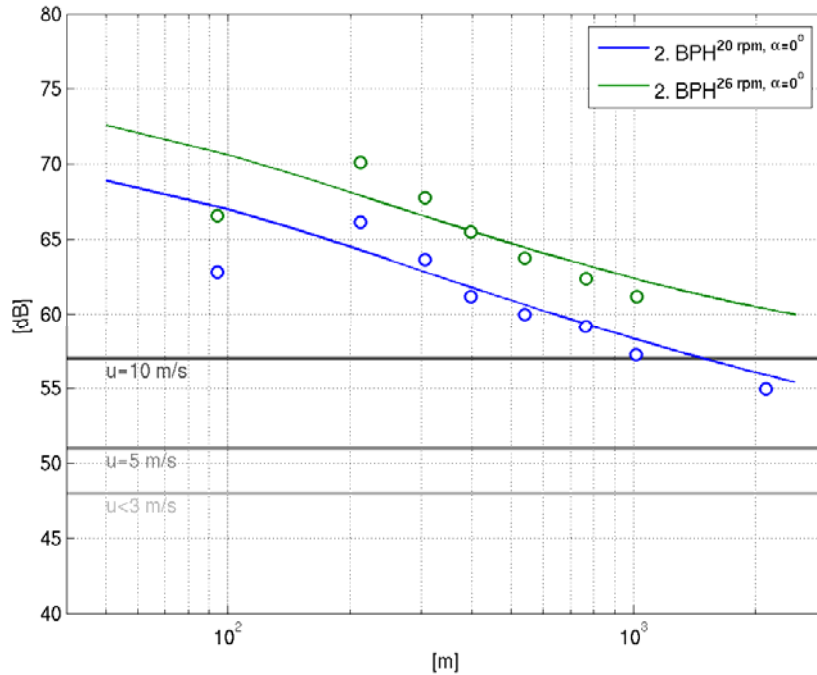
θ – altitude angle to listener

a_m^Q – complex Fourier coefficients of thrust forces

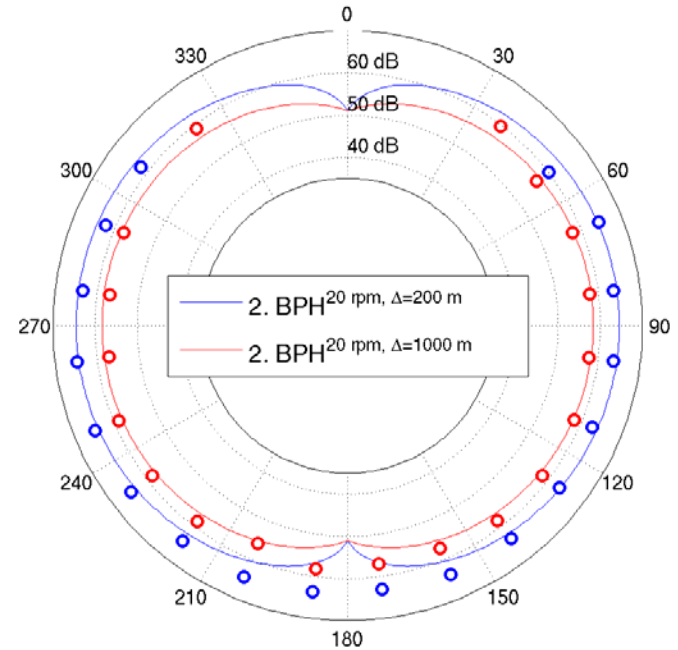
a_m^T – complex Fourier coefficients of torque forces

Comparison between measured and estimated SPL

SPL as a function of distance

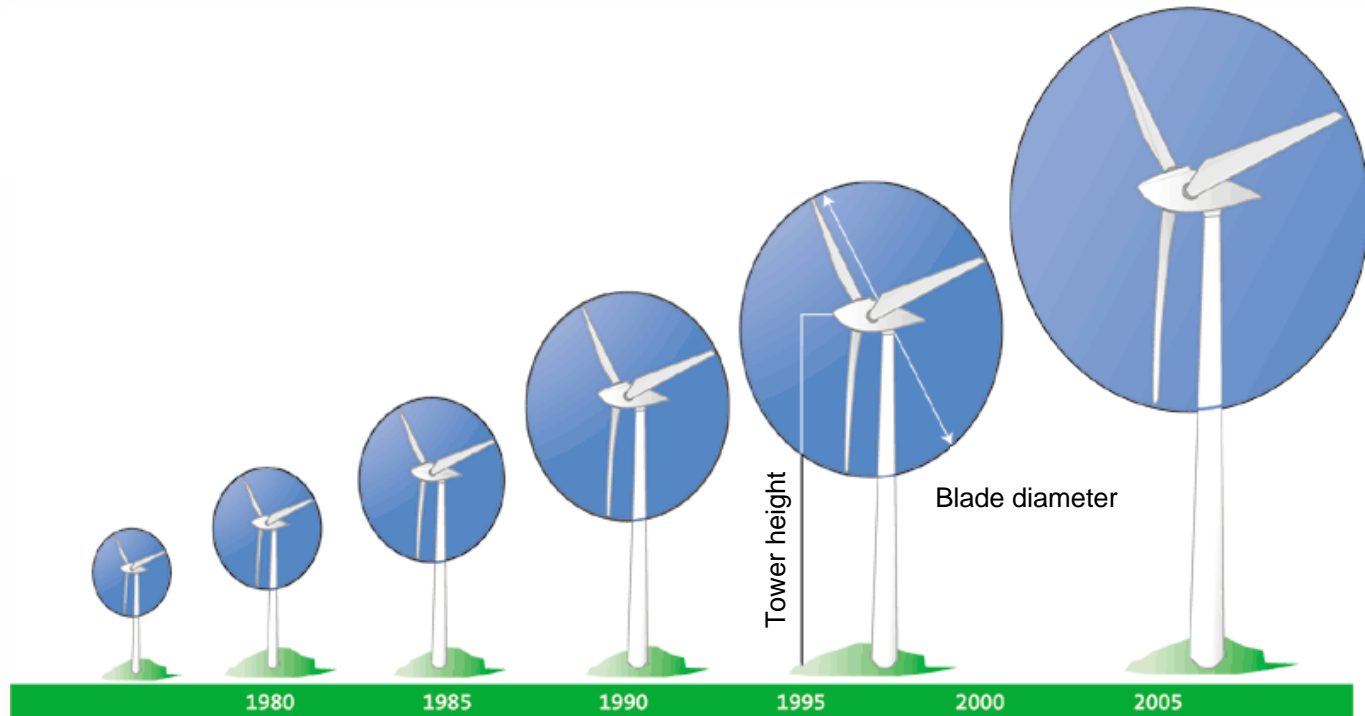


SPL as a function of azimuth



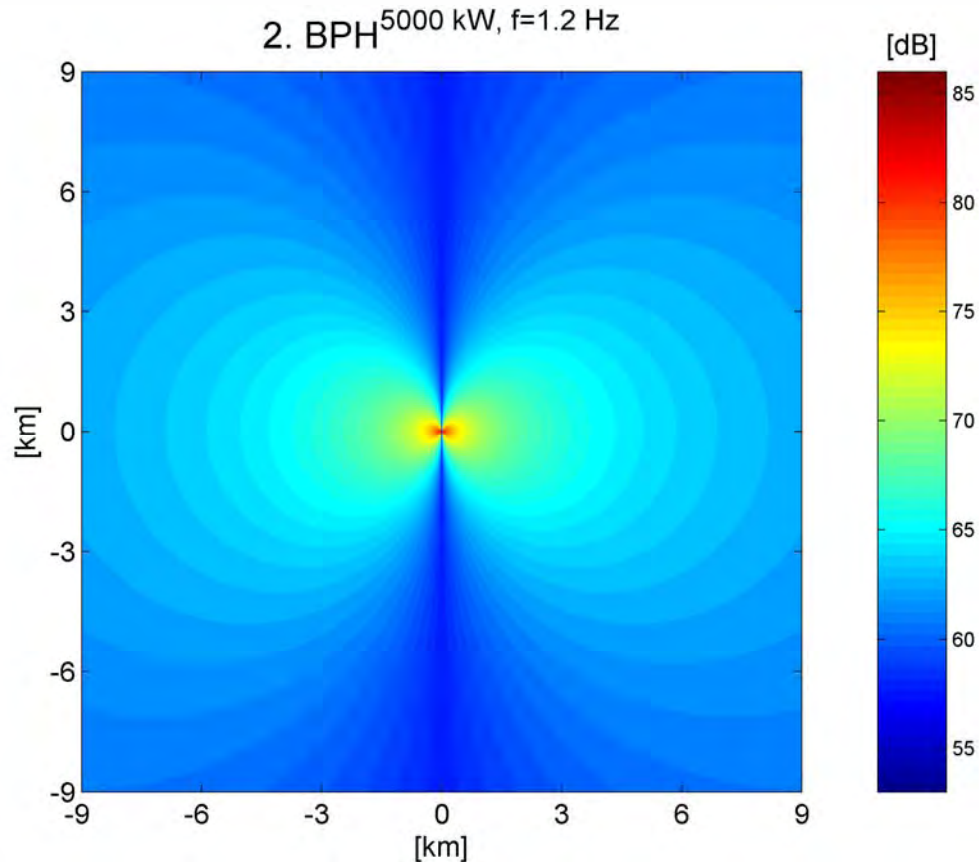
account for surface effects (e.g. reflections) by adding 3 dB to the estimated curves

Estimating the SPL generated by wind turbines

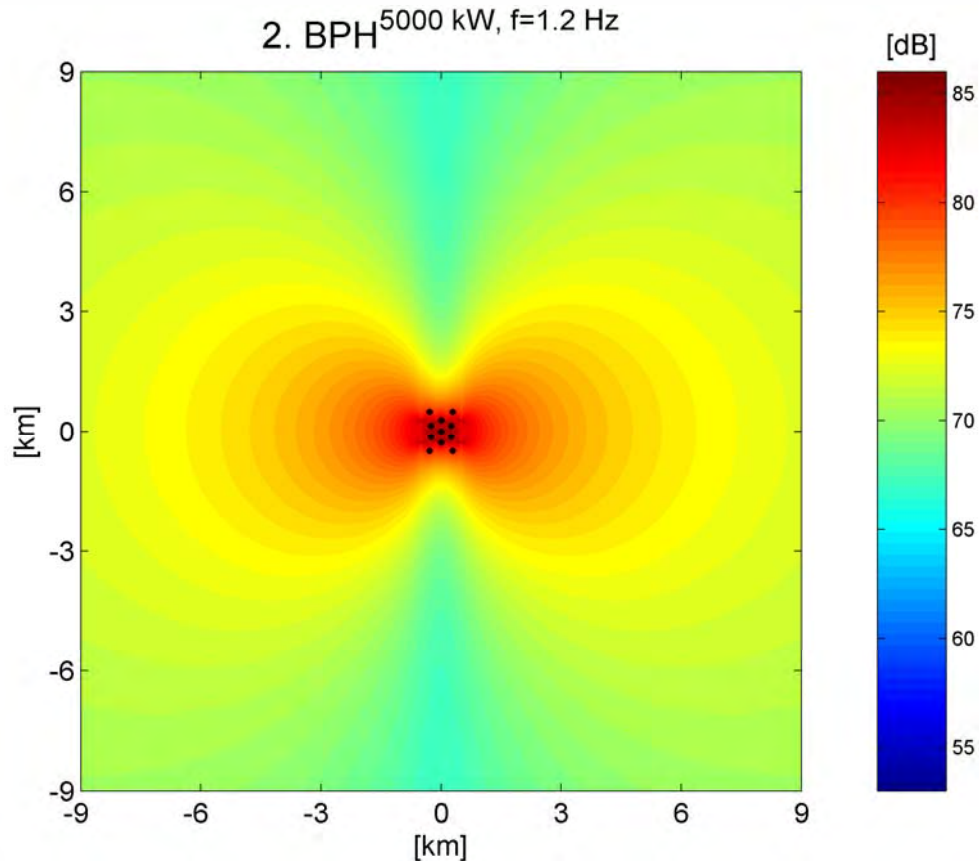


	1980	1985	1990	1995	2000	2005
Power	: 30 kW	80 kW	250 kW	600 kW	1.500 kW	5.000 kW
Blade diameter	: 15 m	20 m	30 m	46 m	70 m	115 m
Tower height	: 30 m	40 m	50 m	78 m	100 m	120 m
Energy production per year	: 35.000 kWh	95.000 kWh	400.000 kWh	1.250.000 kWh	3.500.000 kWh	ca. 17.000.000 kWh

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

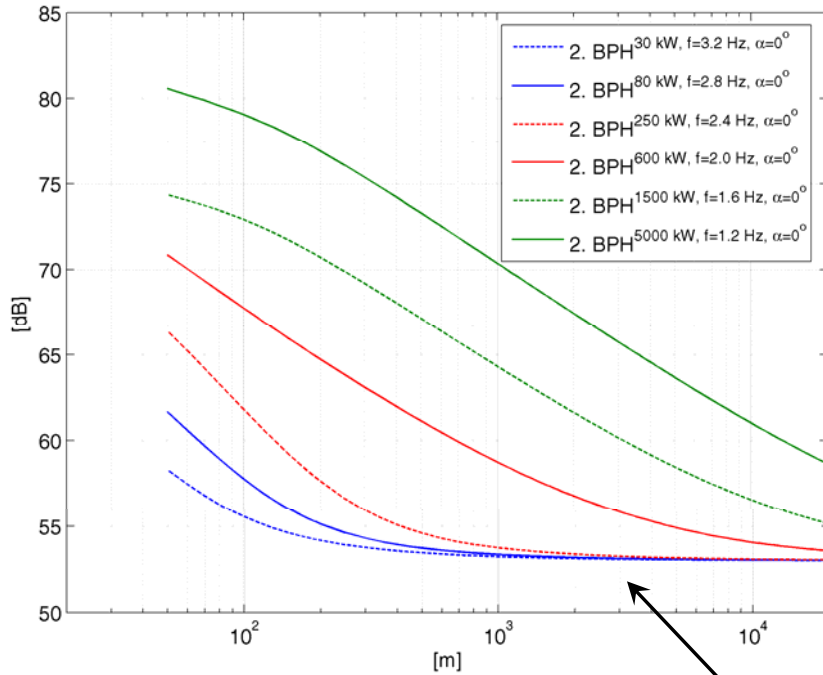


Estimating the SPL generated by (a) large wind turbine(s)

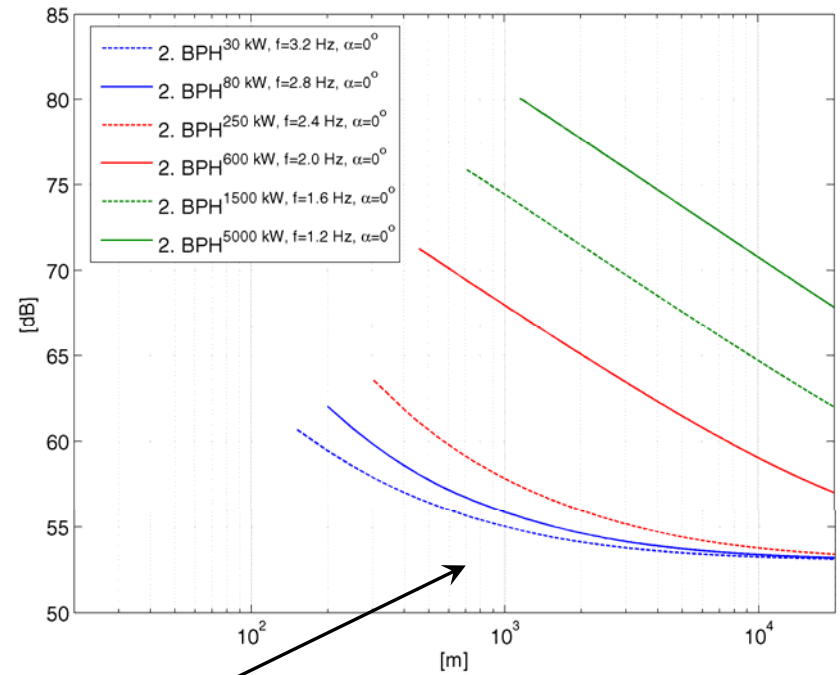


Estimating the SPL generated by Wind Turbines/Farms at ~2 Hz

single wind turbine



11-element wind farm



noise level

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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 $\sim R^{-1}$
 - SPL $\sim \text{rpm}^4$
- 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)