National Renewable Energy Laboratory
Innovation for Our Energy Future

Wind Turbine Spacing in Wind Farms and Sound

BLM WEATS Workshop

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Why is noise an issue?

- Objectionable noise is an impediment to deployment
  - Complaints by residents threaten permitting
  - Projects must comply with established community noise standards (40 – 45 dBA is typical)
- Noise reduced operation (NRO)
  - Energy also lost

Sound Pressure Level

Most common noise measurement (in Decibels – dB)

$$SPL = 10\log_{10}\left(\frac{I}{I_{ref}}\right) = 20\log_{10}\left(\frac{p}{p_{ref}}\right)$$

$$I \propto \frac{1}{r^2} \qquad p \propto \frac{1}{r}$$

r = observer distance

Doubling distance = -3 dB in SPL

Doubling intensity = +3 dB in SPL

Human ear detects around 3 dB change

+10 dB = subjective doubling of perceived loudness

Sound Power Level

$$L_W = 10\log_{10}\left(\frac{W}{W_0}\right) \qquad SPL \approx L_W - 10\log_{10}(2\pi r^2)$$

A-weighting

dB vs. dB(A)

Mimic behavior of human ear

Certain frequencies appear louder

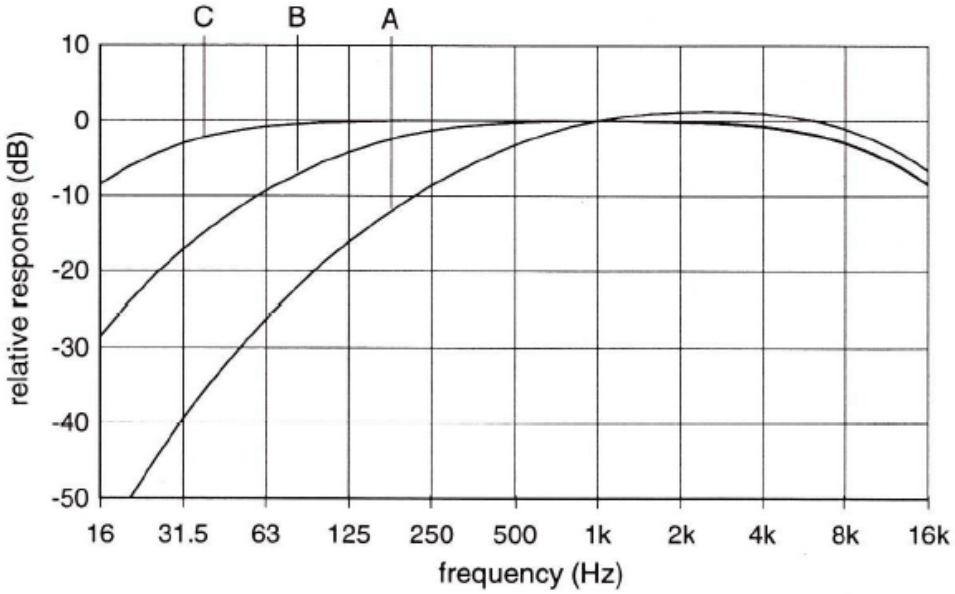
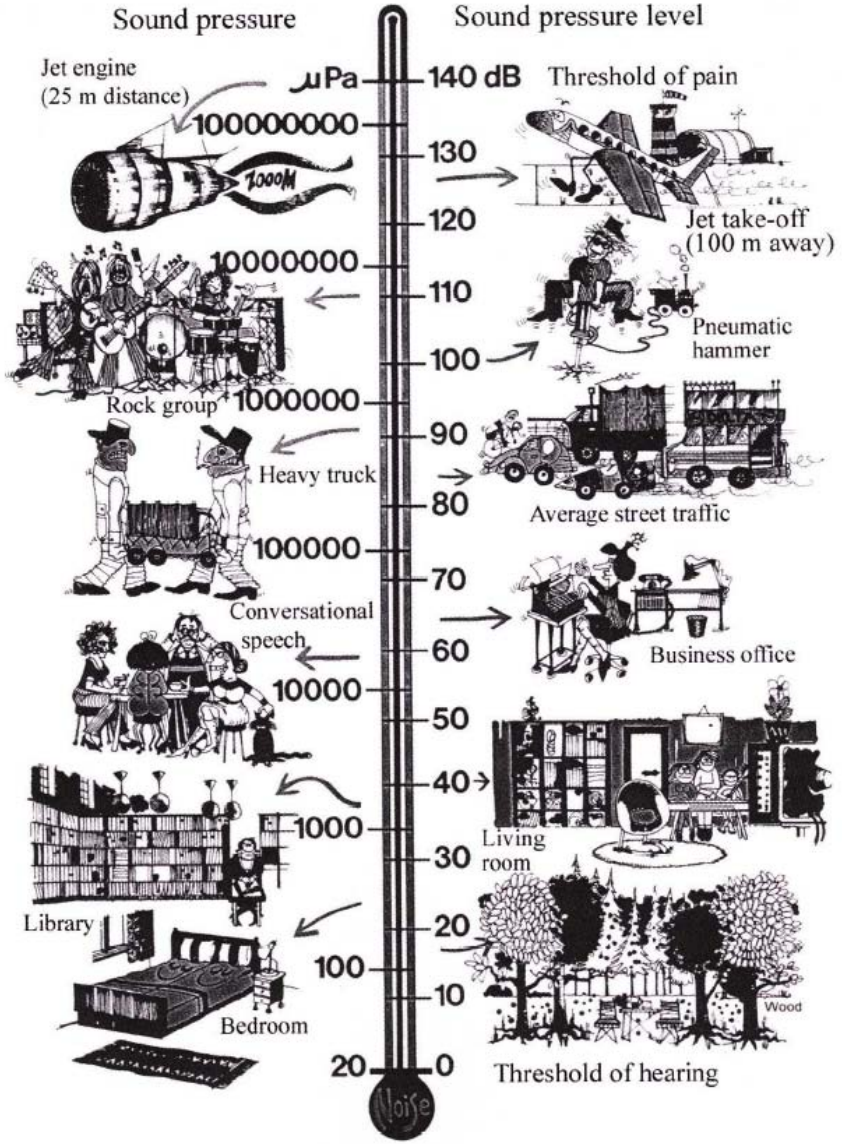
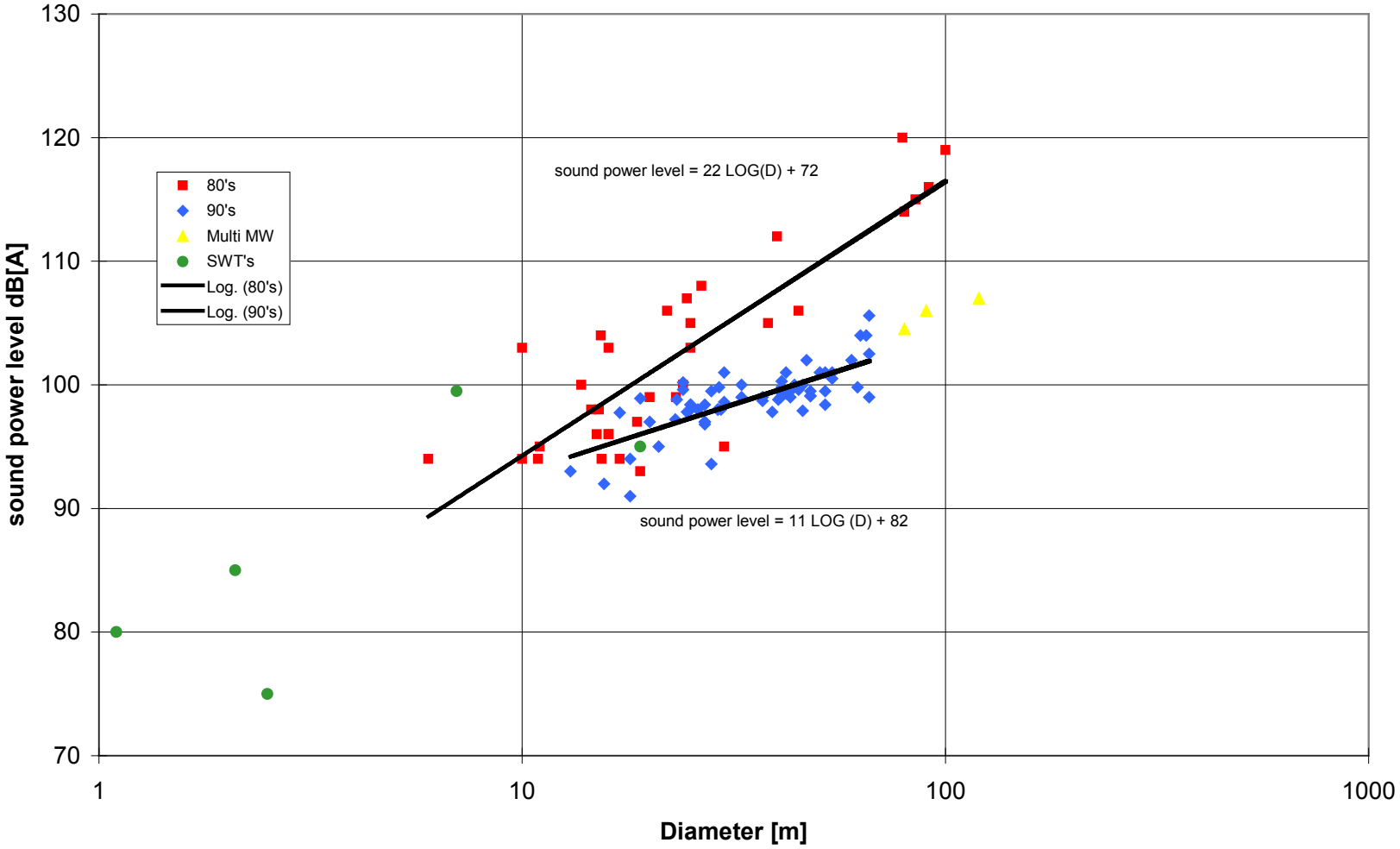


Figure 2.4: Definition of A-, B-, and C-weighting.

Noise and SPL

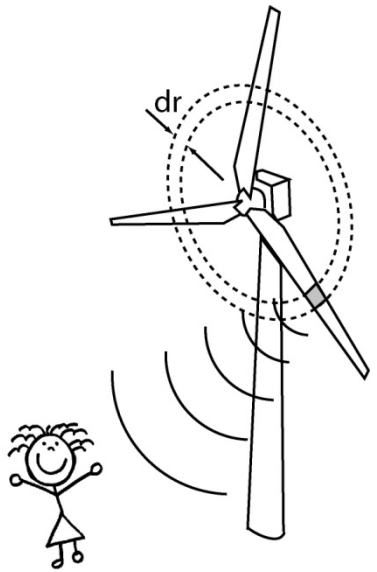


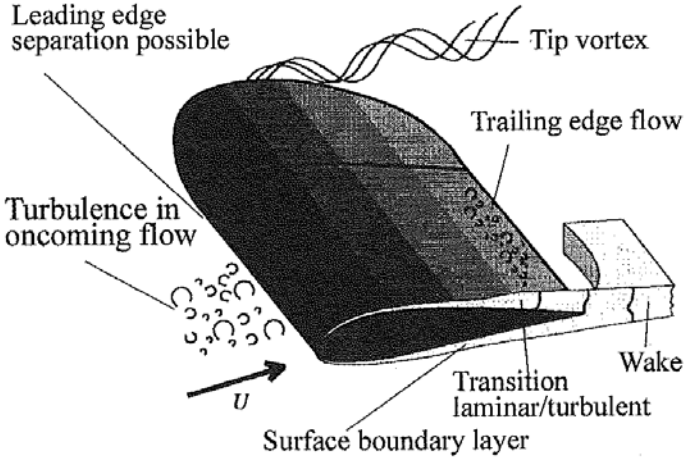
Noise Trends for Large Wind Turbines



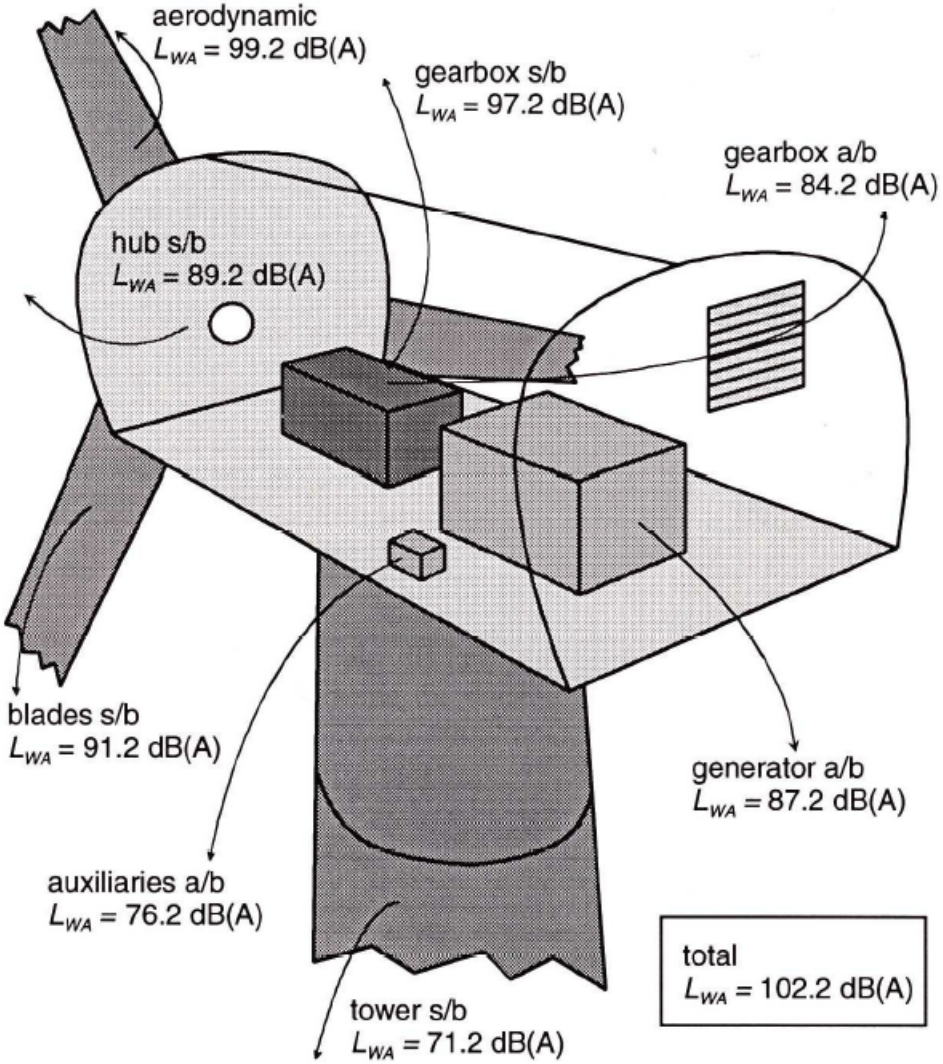
Types of wind turbine noise

- Mechanical
  - Mostly tones
  - Gearbox
  - Generator
  - Tower resonance
  - Blade movement
- Aerodynamic
  - Blades & tips
    - Proportional to V_{tip}^{5}
    - Higher frequency and broadband
  - Tower wake
    - Rotational (low frequency)
    - 1-3 per rev





Relative noise contributions



Typical noise spectra

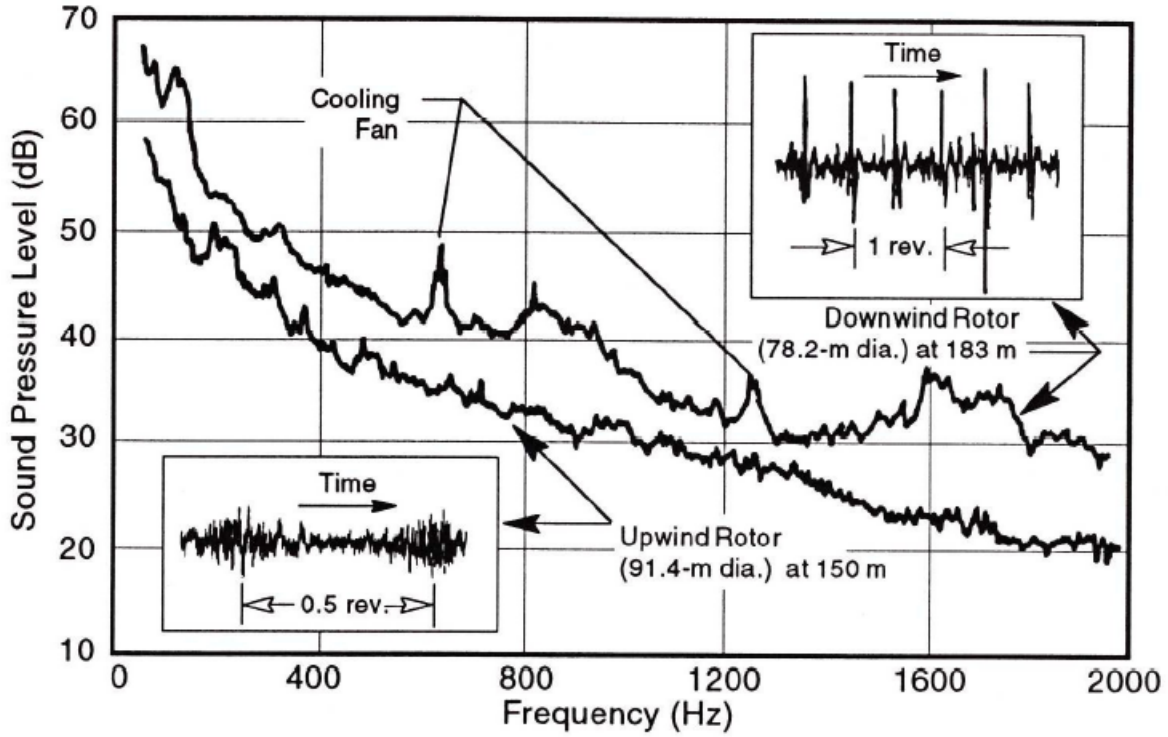
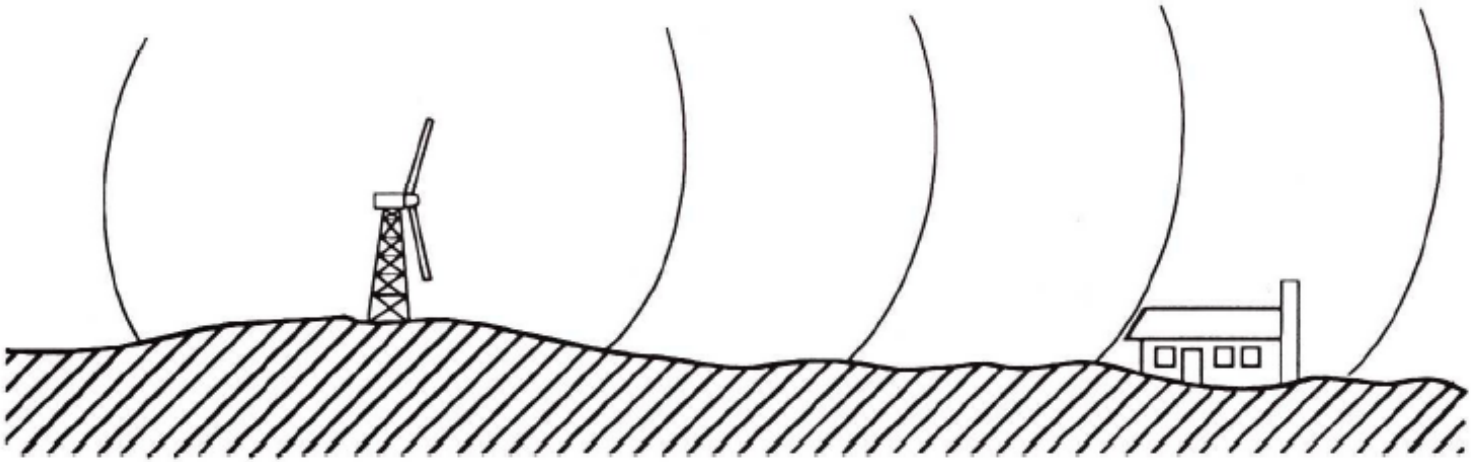


Figure 7-4. Narrow-band noise spectra from large-scale HAWTs with upwind and downwind rotors. (bandwidth = 2.5 Hz)

Noise Regimes

3 different regimes



Noise sources	Propagation paths	Receivers
• Aerodynamic	• Distance	• Ambient noise
• Mechanical	• Wind gradients	• Indoor/outdoor exposure
	• Absorption	• Building vibrations
	• Terrain	• Human perception

Propagation

Humidity

Wind direction and speed

Wind Shear

Turbulence

Terrain

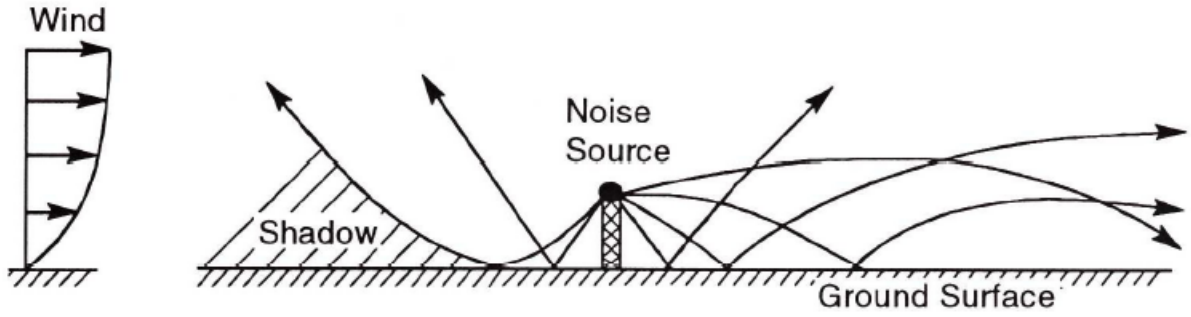


Figure 7-20. Effects of wind-induced refraction on acoustic rays radiating from an elevated point source. [Shepherd and Hubbard 1985]

Noise Ordinances

Varies by place and use

Table 2.4: Noise limits for equivalent sound pressure levels L_{Aeq} (dB(A)) in different European countries [75].

Country	*Commercial*	*Mixed*	*Residential*	*Rural*
Denmark			40	45
Germany				
– day	65	60	55	50
– night	50	45	40	35
Netherlands				
– day		50	45	40
– night		40	35	30

Background/Ambient Noise

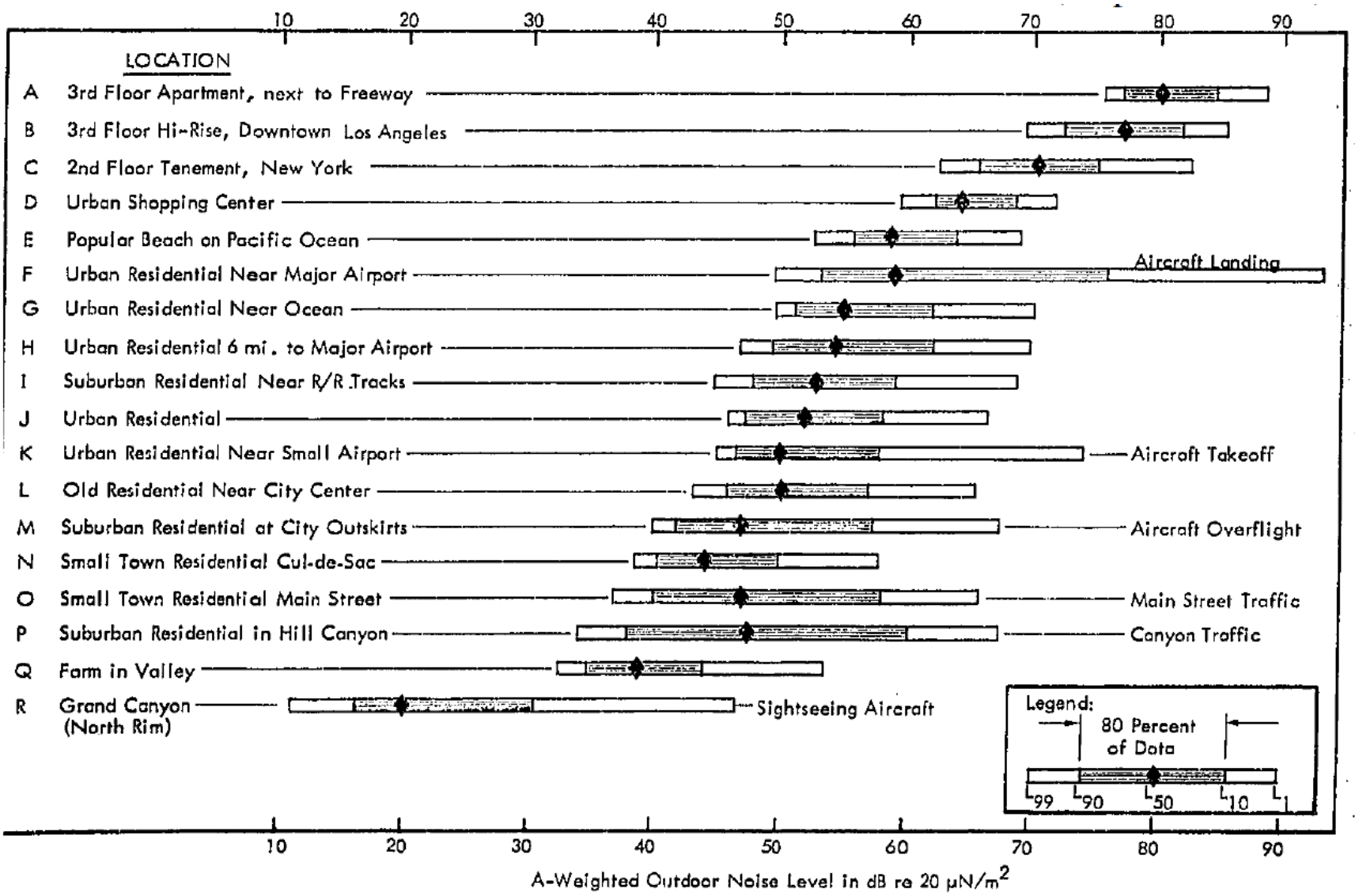


Fig 7 of EPA Report, Daytime Noise

Human Response

Not as predictable as everything else

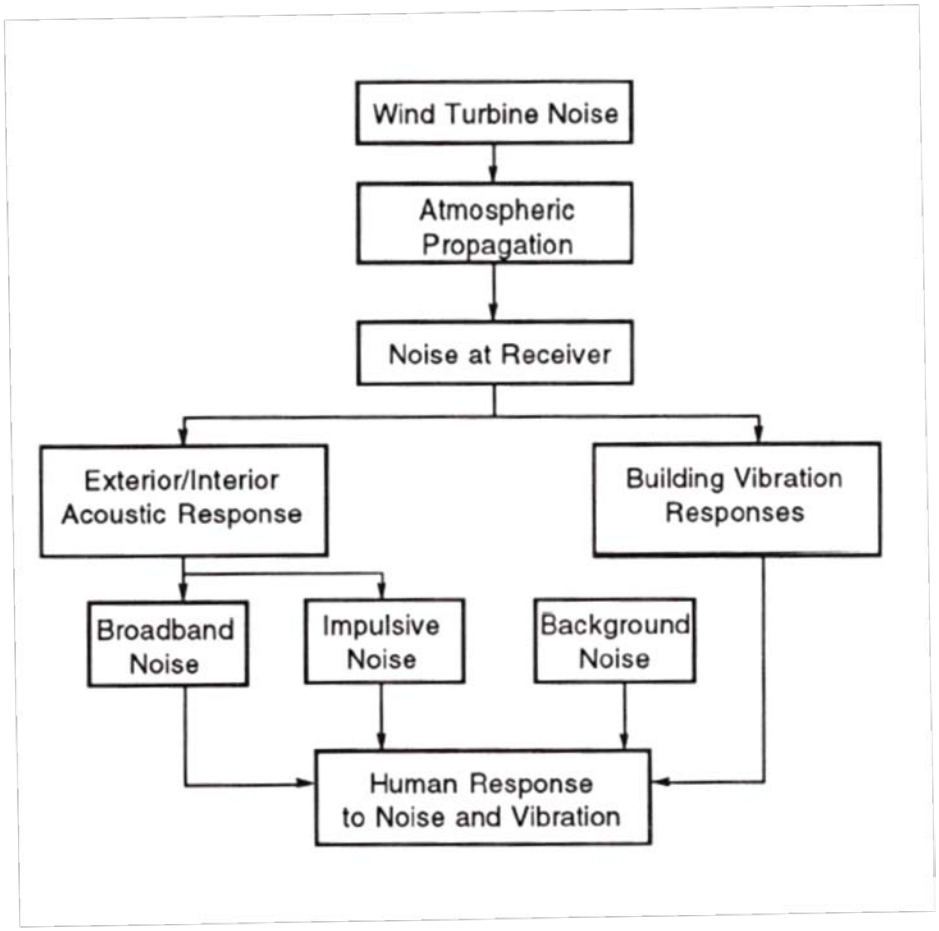


Table 7.1. Estimated Community Response to Noise (ISO 1971)

Amount by which received noise exceeds threshold level (dB)	Estimated community response	
	Category	Description
0	None	No observed reaction
5	Little	Sporadic complaints
10	Medium	Widespread complaints
15	Strong	Threats of community action
20	Very Strong	Vigorous community action

Noise descriptions

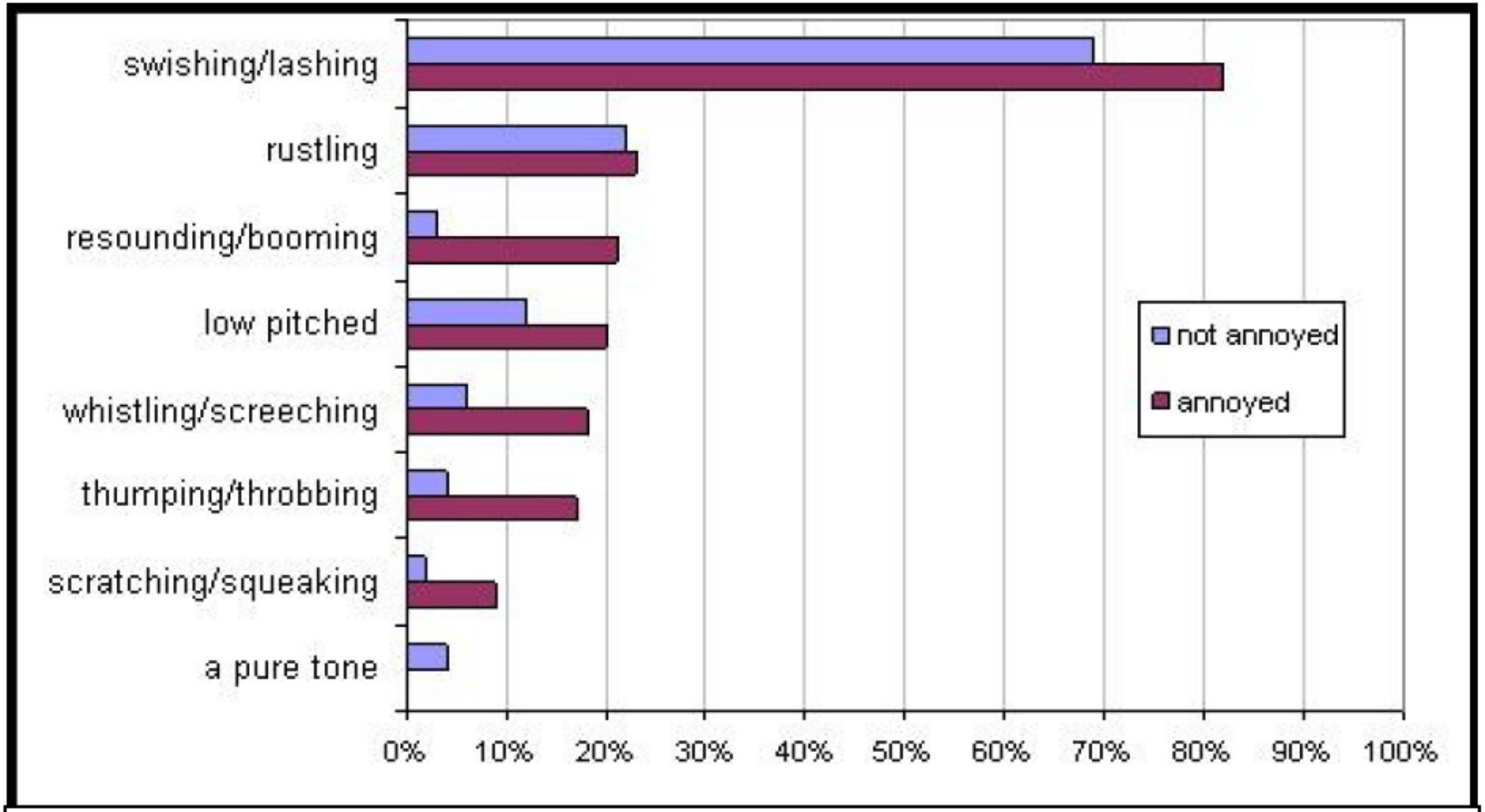
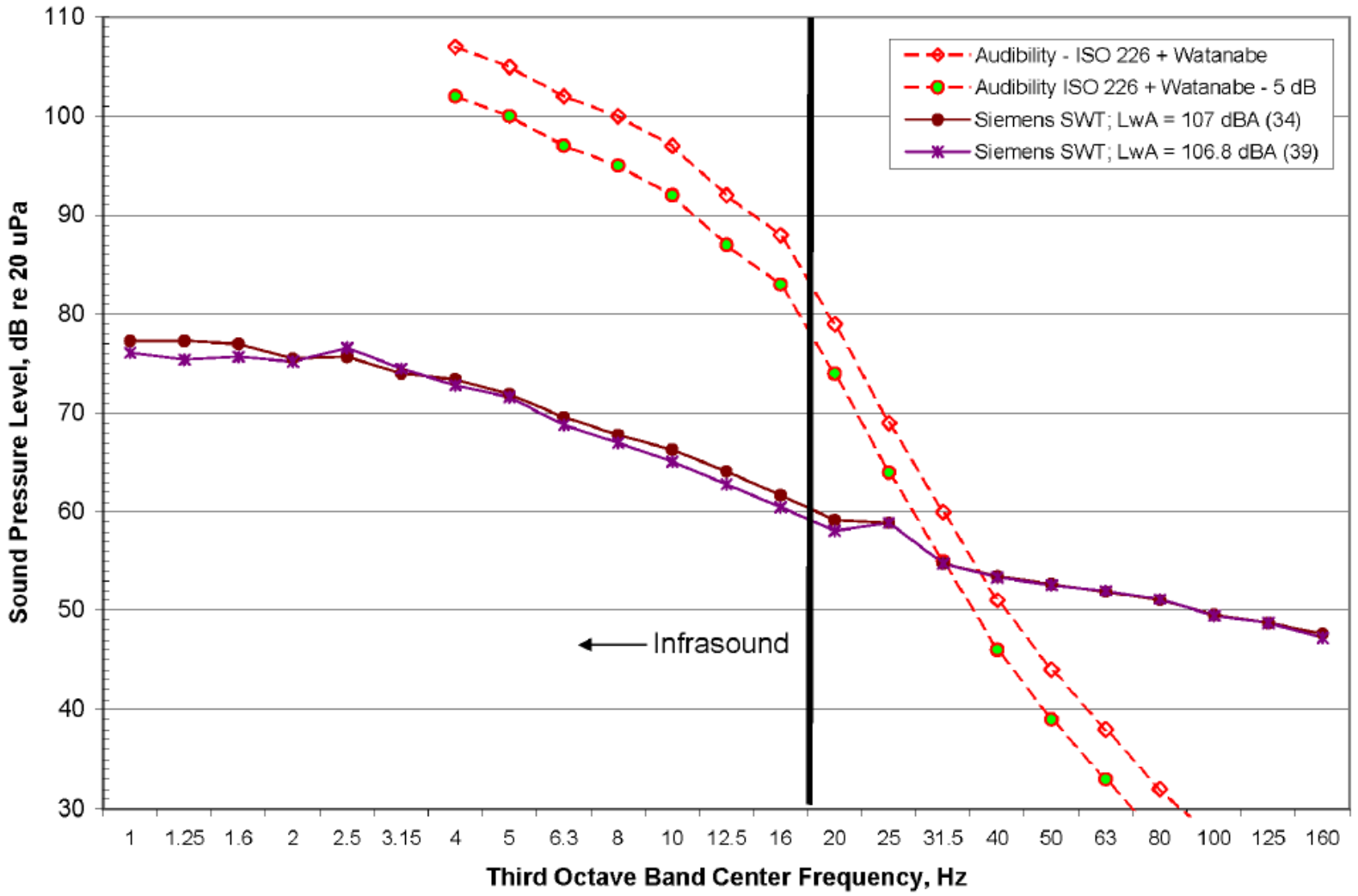


Figure 1: percentage of respondents that think the description fits the wind turbine sound they hear at home (based on [11])

Low Frequency Noise and Infrasound

Figure 8.1-1 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria

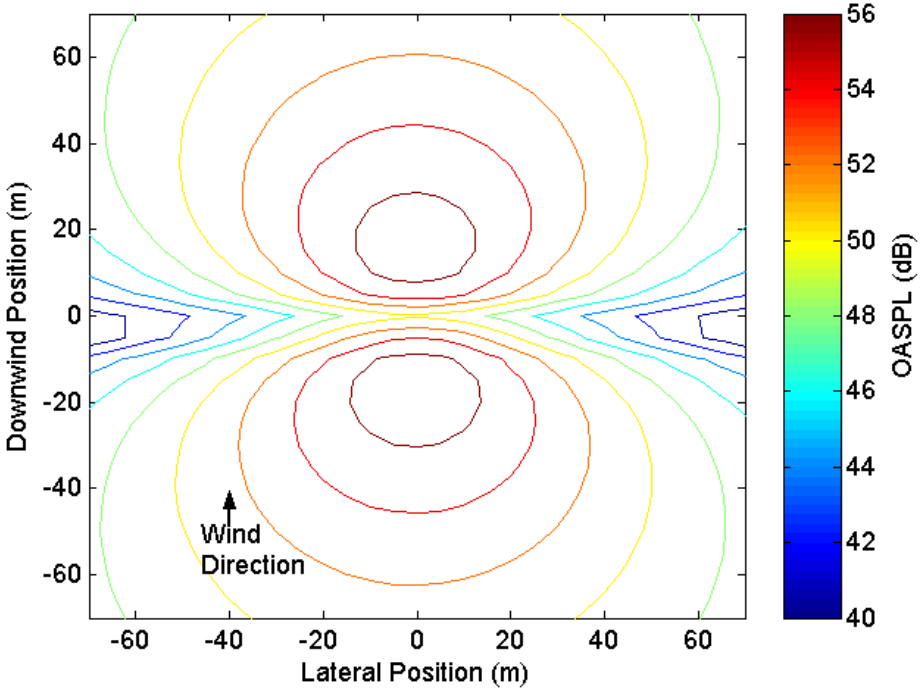


Noise reduction

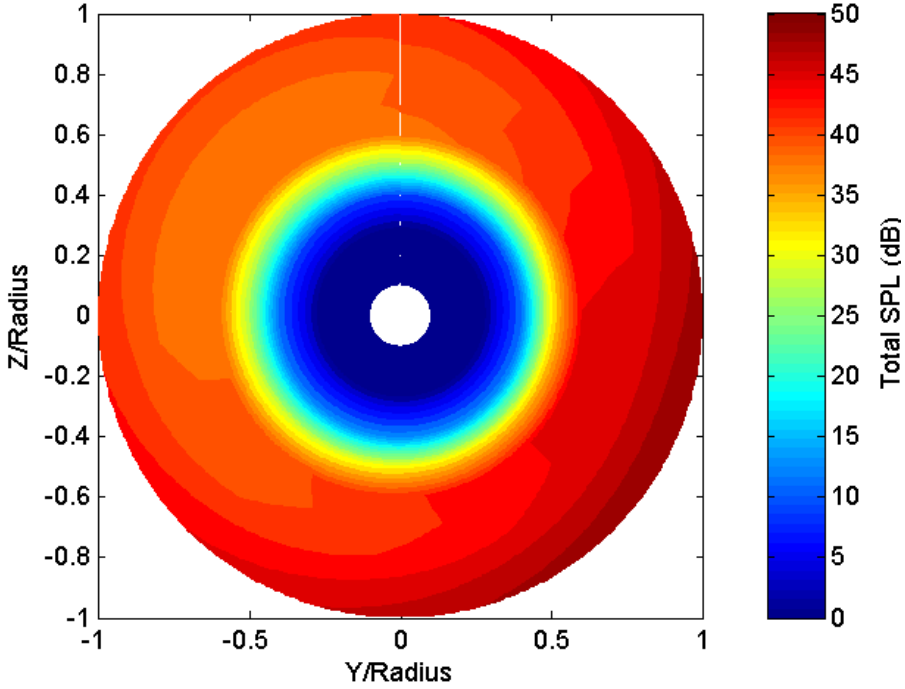
- Move turbines farther away
  - Offshore
  - Low frequencies travel farther
- Mechanical
  - Isolation
  - Insulation
- Aerodynamic
  - Lower tip speed (Noise Reduced Operation)
  - Modify Blade Shape
    - Sharp trailing edges

Observer location influence

Noise Footprint - Directivity



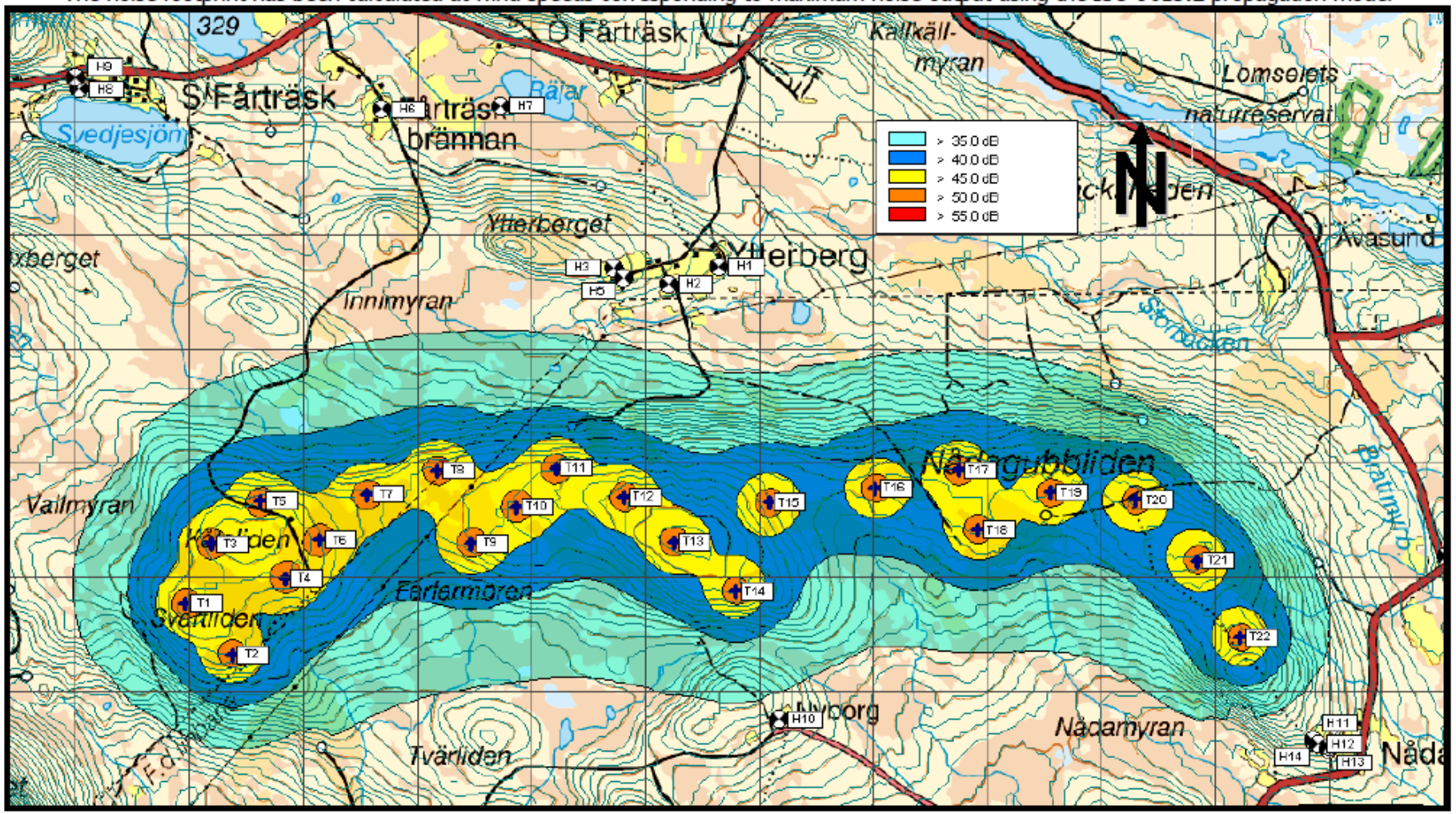
Rotor Plane – Doppler Amplification



AOC 15/50

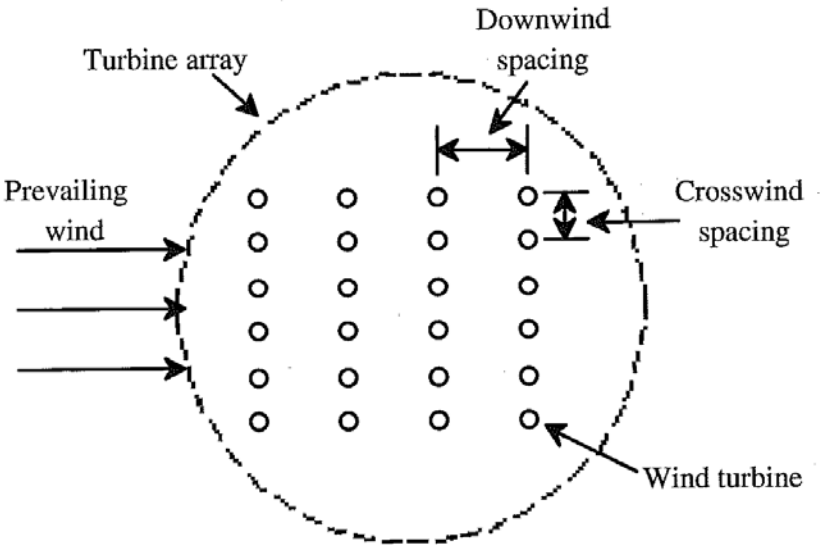
Wind Plant Noise Footprint

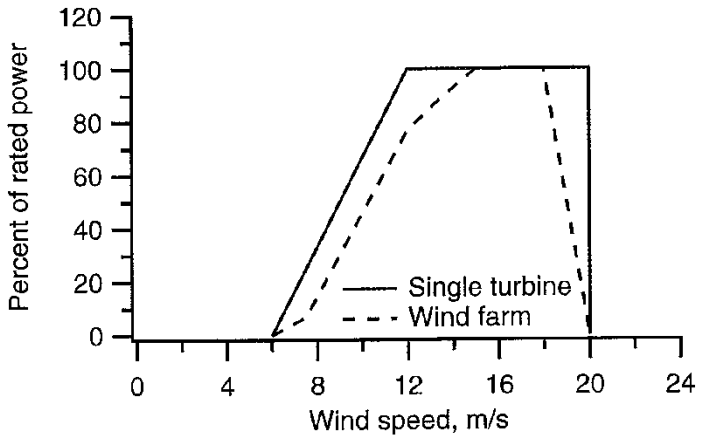
Figure 1 **Predicted Noise Footprint for Proposed Wind Farm**
Grid Intervals at 1 km
The L_{Aeq} descriptor has been used
The noise footprint has been calculated at wind speeds corresponding to maximum noise output using the ISO-9613:2 propagation model



Wind Farm Layout Issues

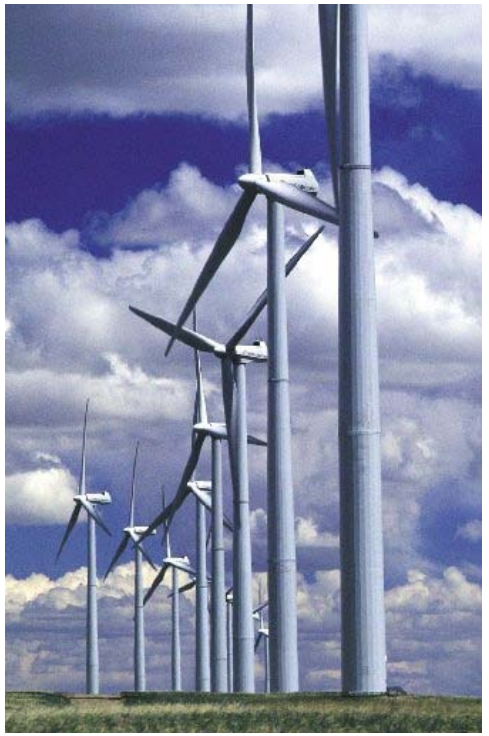
- Optimal spacing/layout
  - Power
  - O&M
- Design Constraints
  - Turbine interactions
  - Atmospheric conditions
  - Terrain
  - Electrical Interconnect & substation
  - Roads
  - Environmental impacts
  - Land Rights
  - Wind Rights





Why is layout design important?

- Optimal power production
  - Example
    - 200 - 2 MW wind turbines
    - 1.26 x 10^9 kWh/year (36% capacity factor)
    - 5 ¢/kWh
    - 1% change in efficiency OR
    - ~0.1 m/s change in annual wind speed
    - = $630k/year = $12.6 million/farm lifetime
  - 10% underproduction for existing farms is common ($$!)
- O&M costs
- Near-term forecasting
  - Pricing
  - Load matching



Wind Farm Wakes

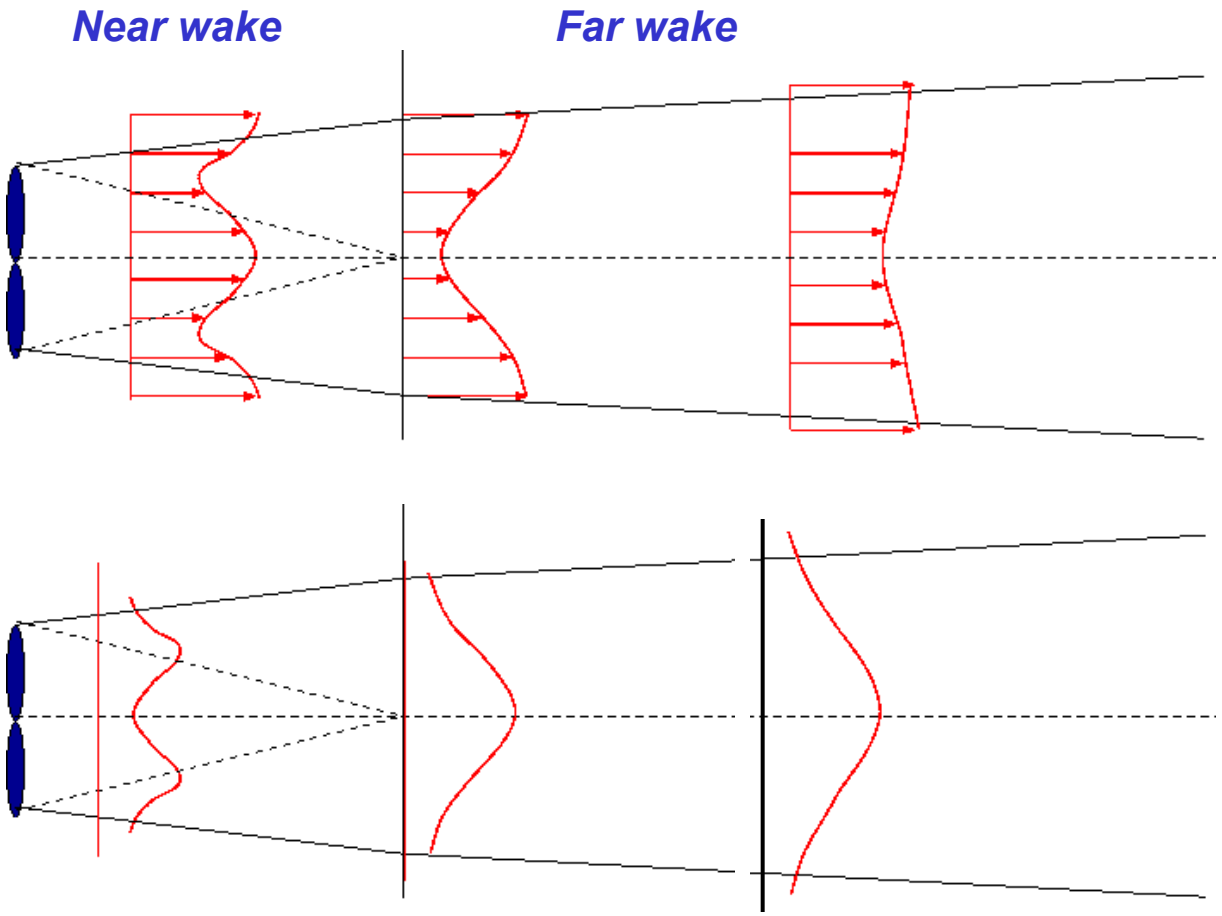
Spacing Distance

Mean wind speed

Power Losses

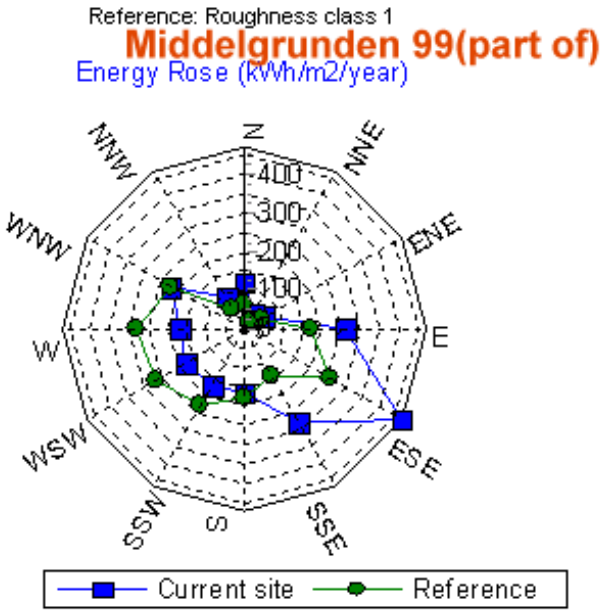
Turbulence intensity

O&M Costs

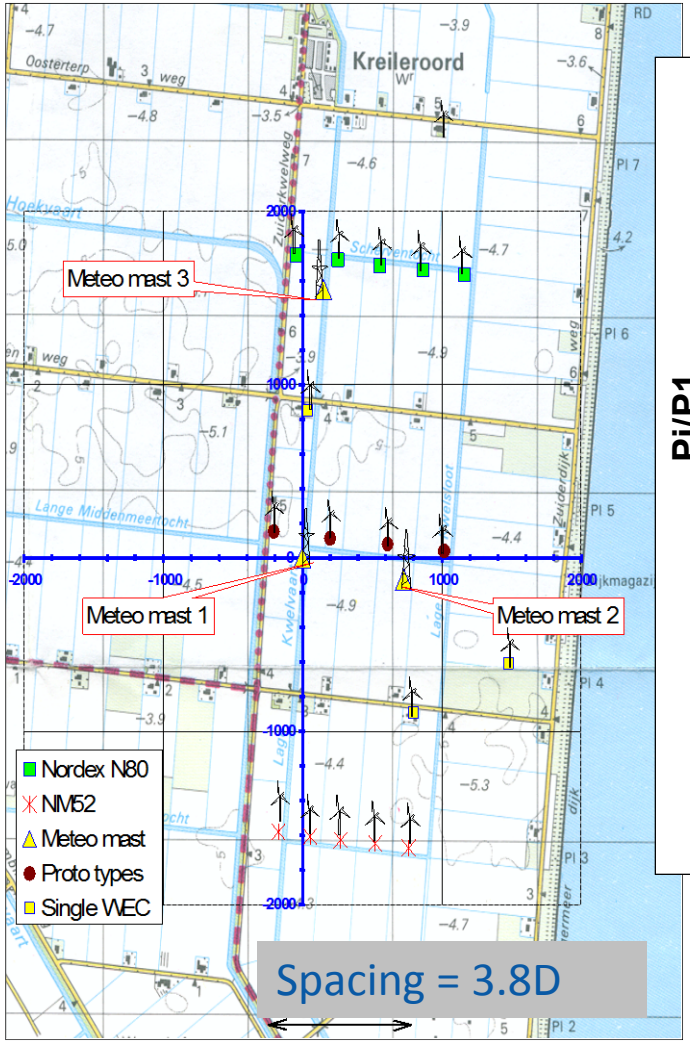


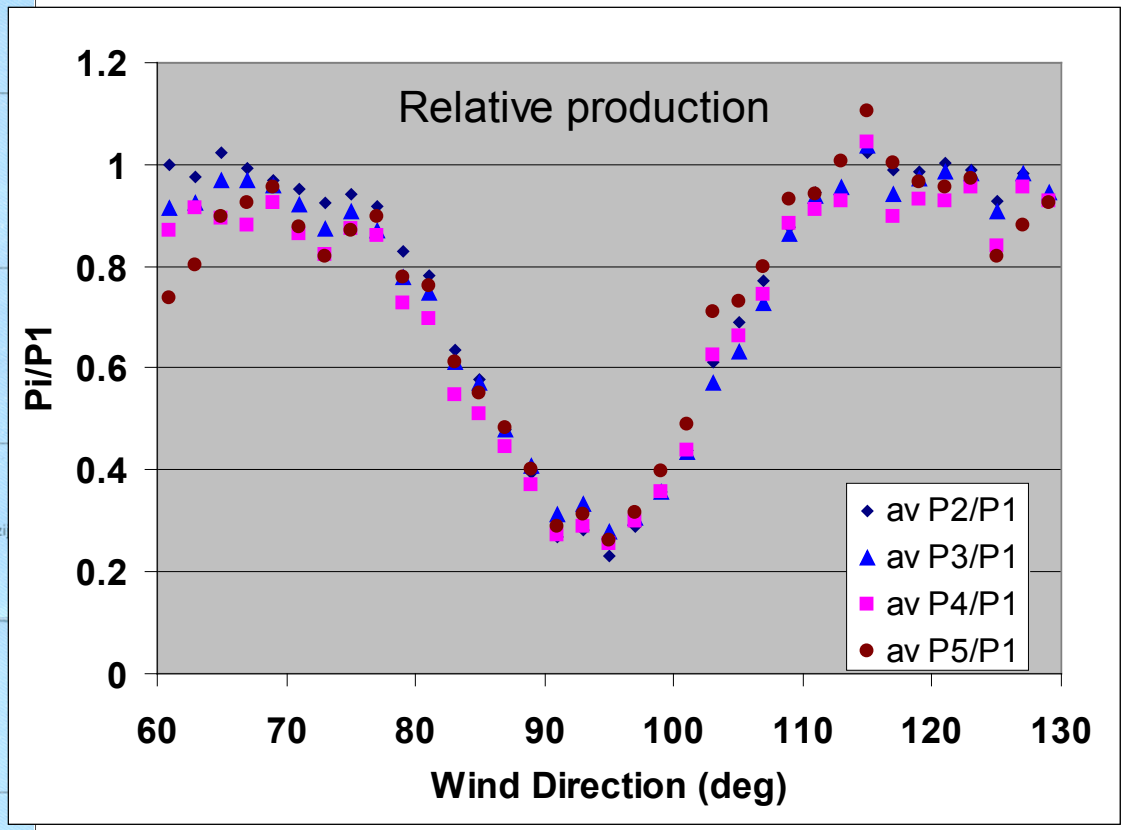
Rule of thumb - 10D downwind, 3D crosswind

Dominant Wind Direction



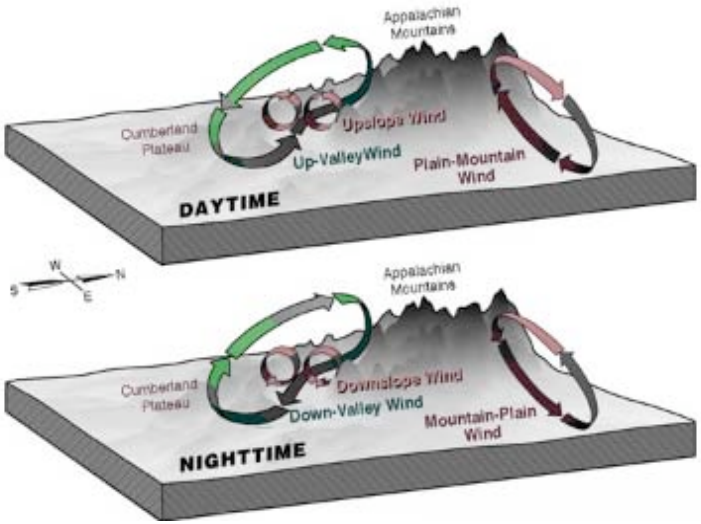
Power Losses





Biggest loss between row 1 & 2

Complex terrain



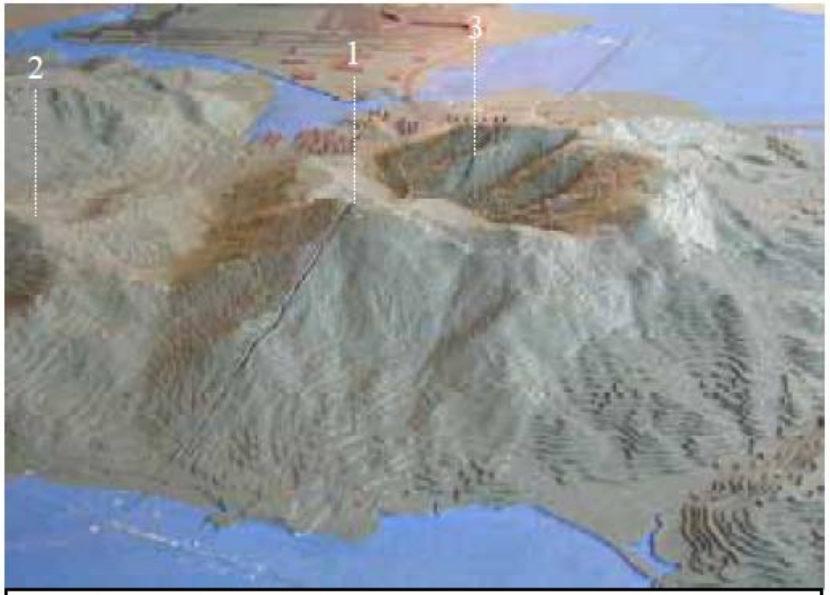


Fig.13. Scale model of mountainous terrain (Lantau Island) with multiple peaks and valleys. For wind tunnel study.

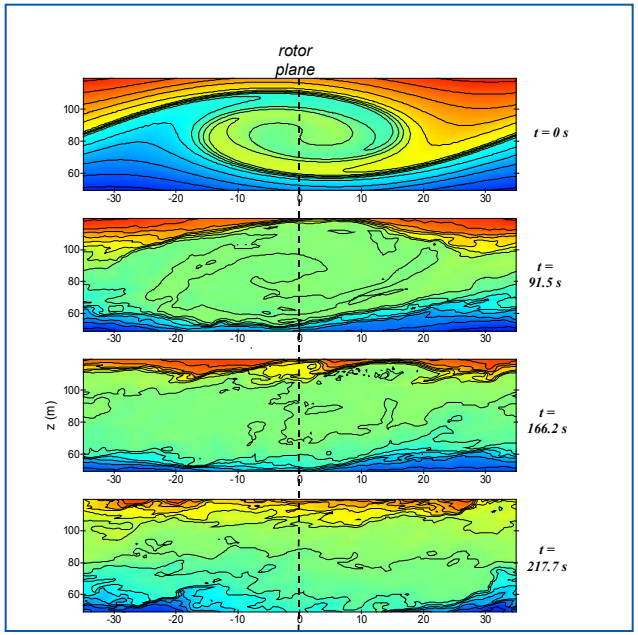
Atmospheric Stability

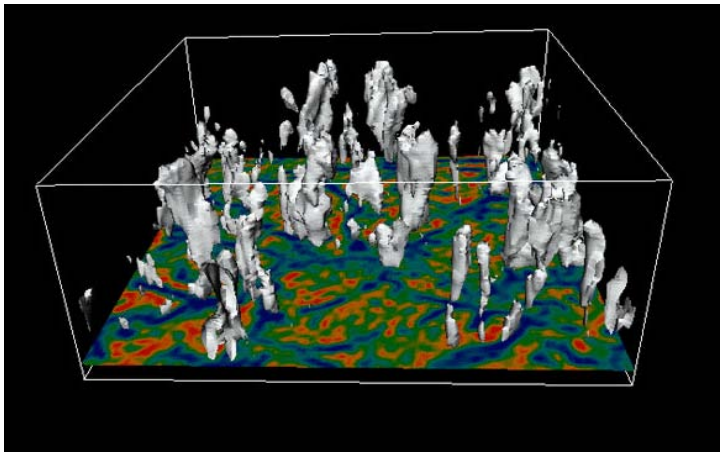
Diurnal variation

Influences

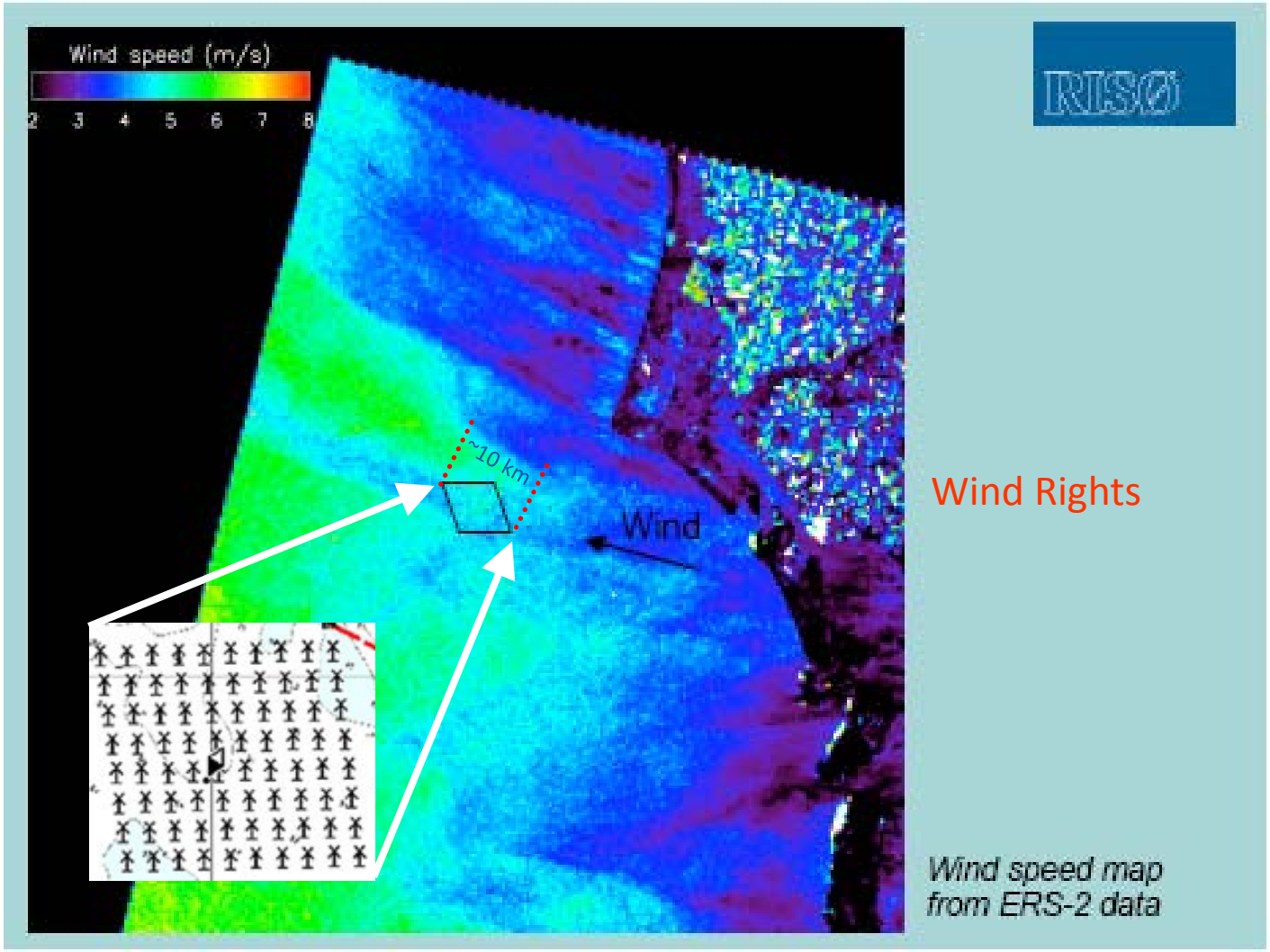
- Turbulence
- Wake propagation
- Most important at
  - greater hub heights > 50 m
  - low wind speeds < 10m/s
  - low surface roughness

Starting to be considered important for wind farm models





Large Scale Impacts



Wind Farm Modeling Tools

- Engineering Models
  - Linear or Semi-Linear
  - WAsP,WindFarmer, WindPro, etc
- Computational Fluid Dynamics (CFD)
  - Reynolds Averaged Navier Stokes (RANS)
    - Turbulence modeled
    - MetoDyn, Ventos, WindSim, RaptorNL – Mainly resource assesment
    - Fast
  - Detached Eddy Simulation (DES)
    - Hybrid RANS/LES
  - Large Eddy Simulation (LES)
    - Most turbulence calculated
    - Expensive
  - Direct Numerical Simulation (DNS)

Industry

Research

Questions?