INTRODUCTORY LECTURE

Wind Resource Assessment in Complex Terrain, a Wind Tunnel Approach

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Outlines

- What is a complex terrain? Why is it of interest?
- The physical modeling
- Dimensionless numbers
- Boundary conditions reproduction
- Applications (mountainous, forest, urban areas)

What is a complex terrain? Why is it of interest?

- Newly installed turbines are mainly **onshore** (90% in 2013)

- Complex terrains are attractive for **availability** and **high wind** speed:
  - cliffs,
  - mountains with steep slopes,
  - forest,
  - urban area

http://www.donqi-global.co.uk/

http://juliaharte.wordpress.com

Picture from « Ouest-France »

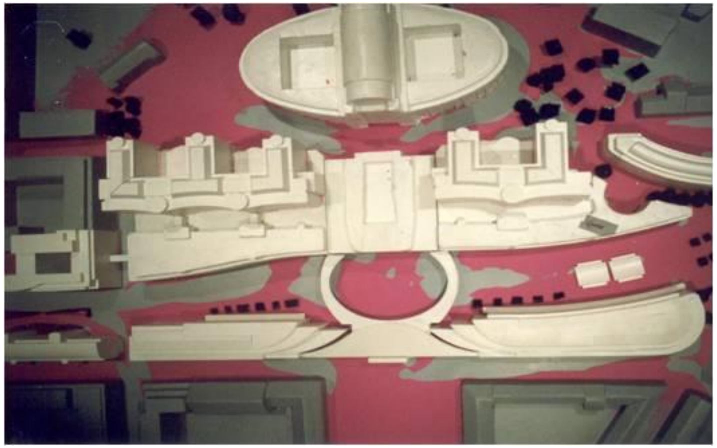
What is a complex terrain? Why is it of interest?

- However, complex terrain = complex flow behavior:
  - high turbulence level, steep velocity gradients, flow separation, vortex shedding, roughness transition …

- So the wind resource is difficult to assess:
  - field measurements: lack of spatial resolution
  - CFD: difficult, simple turbulence modeling may be unsufficient

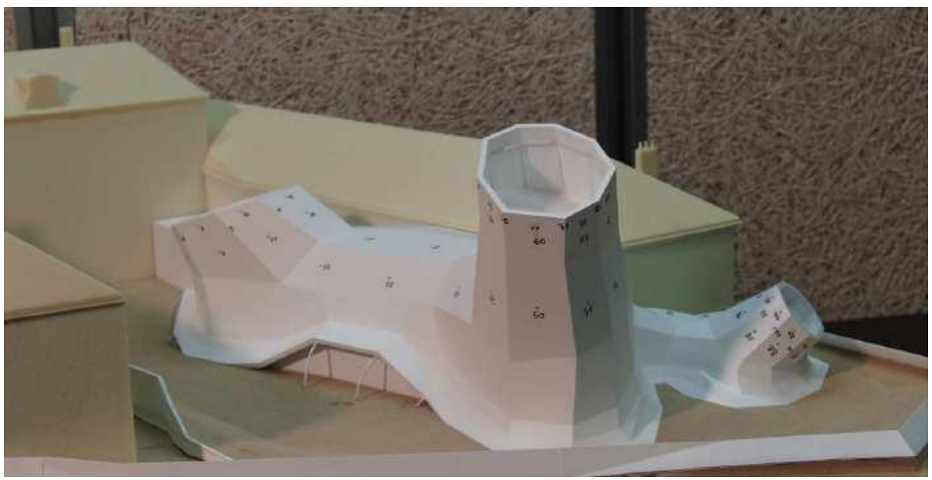
- Wind tunnel modeling can be a useful tool

The physical modeling



Pedestrian comfort:
European parliament (VKI)

Aerodynamic design of the Belgium polar station (VKI)



Wind loading on buildings (Univ. Orléans)

Urban dispersion (Univ. Hamburg)

The physical modeling

- Similarity criteria
  - "General similarity of two systems requires **geometric** similarity, **kinematic** similarity, **dynamic** similarity, **thermal** similarity, and similarity of the **boundary conditions**." *J.J. Cermak AIAA 1971 vol.9 NO.9*

→ Geometric similarity

→ Dimensionless numbers

→ Boundary conditions reproduction

Dimensionless numbers

- Dimensionless equations:
  - Equation of motion

$$\frac{\partial \overline{U}_i^{\,*}}{\partial t^*} + \overline{U}_j^{\,*} \frac{\partial \overline{U}_i^{\,*}}{\partial x_j^{\,*}} + 2\varepsilon_{ijk}\Omega_j^{\,*}\overline{U}_k^{\,*} \cdot \left[\frac{L_0\Omega_0}{U_0}\right] = -\frac{\partial \overline{P}^{\,*}}{\partial x_i^{\,*}} - \left[\frac{\Delta \overline{T}_0}{\overline{T}_0}\frac{L_0 g_0}{U_0^{\,2}}\right]\Delta \overline{T}^{\,*} g^* \delta_{i3}$$

Rossby number bulk **Richardson** number

$$+\left[\frac{\upsilon_0}{U_0 L_0}\right]\frac{\partial^2 \overline{U}_i^{\,*}}{\partial x_k^{\,*}\partial x_k^{\,*}} + \frac{\partial \left\langle -u_i' u_j' \right\rangle^*}{\partial x_j^{\,*}}$$

Reynolds number

with:

- $u = \overline{U} + u'$
- Boussinesq approximation

Dimensionless numbers

- Dimensionless equations:
  - Conservation of energy

$$\frac{\partial \overline{T}^*}{\partial t^*} + \overline{U}_i^* \frac{\partial \overline{T}^*}{\partial x_i^*} = \left[\frac{k_0}{\rho_0 C_{p0} \upsilon_0}\right]\left[\frac{\upsilon_0}{L_0 U_0}\right] \frac{\partial^2 \overline{T}^*}{\partial x_k^* \partial x_k^*}$$

Prandtl number

$$+ \frac{\partial \left\langle -\theta' u_i' \right\rangle^*}{\partial x_i^*} + \left[\frac{U_0^{\,2}}{C_{p0} (\Delta \overline{T})_0}\right]\left[\frac{\upsilon_0}{L_0 U_0}\right] \phi^*$$

$$T = \overline{T} + \theta'$$

Eckert number

Dimensionless numbers

- Dimensionless numbers:
  - Rossby number (Ro)
  - Richardson number (Ri)
  - Reynolds number (Re)
  - Prandtl number (Pr)
  - Eckert number (Ec)

Dimensionless numbers

- Rossby number (Ro):

$$Ro = \frac{U_0}{L_0 \Omega_0} = \frac{\text{local acceleration}}{\text{Coriolis acceleration}}$$

  - depend on the dimension: Coriolis force negligible for L_0 <<
  - cannot be reproduced in a wind tunnel:
    - the effects of Earth rotation are neglected
    - dimension reproduced has to be kept small: **micro-scale** of the order of 5-10 km (depend on authors)

  → **relaxed**

Dimensionless numbers

- bulk Richardson number (Ri):

$$Ri = \frac{\text{boyancy forces}}{\text{inertial forces}} \quad = \frac{\left(\Delta \overline{T}\right)_0}{\overline{T}_0} \frac{L_0 g_0}{U_0^{\ 2}}$$

  - indication of the stability conditions of the atmosphere
  - thermal stratification possible but challenging in the wind tunnel:
    - only **neutral conditions** are reproduced in most of the cases

    → **relaxed**

Dimensionless numbers

- Reynolds number (Re), the problem…

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{U_0 L_0}{\upsilon_0}$$

– indication of the state of the ABL (laminar, turbulent)

– for a given scaling factor $\lambda = \frac{L_{\text{model}}}{L_{\text{real}}}$, the wind speed in the wind tunnel has to be multiplied by $\frac{1}{\lambda}$ to keep the same Reynolds number

→ for example in air:

		field	wind tunnel (1/200 scale)
	L	20 m	0.1 m
	U	5 m/s	**1 000 m/s !!!!**
	Re	$6.4\ 10^6$	$6.4\ 10^6$

Dimensionless numbers

- Reynolds number (Re), relaxation:
  - "Geometrically similar flows are similar at all sufficiently high Reynolds numbers", a minimum Reynolds number ensures invariance of the flow pattern and the drag coefficient
    - minimum Reynolds number (Re > 10 000)
  - however
    - the Reynolds number independency needs to be checked
    - risk of "relaminarization" close to the surface
      - minimum roughness Reynolds number $\frac{u^* z_0}{\upsilon} > 5$
    - dissipation scales are not respected

    → **relaxed**

Dimensionless numbers

- Prandlt number (Pr):
  - properties of the fluid
  - air is used to model air

    → **satisfied**

$$\mathrm{Pr} = \frac{\text{Momentum diffusivity}}{\text{Thermal diffusivity}} = \frac{k_0}{\rho_0 C_{p0} \upsilon_0}$$

- Eckert number (Ec):
  - property of the fluid + Reynolds number
  - the similarity does not depend strongly upon Eckert number until the flow approach the speed of sound

    → **relaxed**

$$\mathrm{Ec} = \frac{\text{kinetic energy}}{\text{enthalpy}} = \frac{{U_0}^2}{C_{p0} (\Delta \overline{T})_0}$$

Boundary conditions reproduction

- Characteristics of the atmosphere to be reproduced in the wind tunnel for a given site:
  - velocity profile
  - turbulence profile
  - turbulent spectra
  - turbulent length scale profile

Often, not enough field data to have the exact local conditions

→Norms based on empirical observations: ESDU, VDI, Eurocode

Boundary conditions reproduction

- Velocity profile (neutral conditions)

  – logarithmic law:

  (derived from NS,
  valid in the surface layer)

$$\frac{\overline{U(z)}}{u^*} = \frac{1}{\kappa}\ln\left(\frac{z-d}{z_0}\right)$$

U: mean velocity
z: height
u*: friction velocity
z_0 aerodynamics roughness length
d: displacement height
κ: von Karman constant

accounts for the terrain roughness

  – power law:

  (engineering approach,
  valid for all the ABL)

$$\frac{\overline{U(z)}}{U_R} = \left(\frac{z-d}{z_R-d}\right)^{\alpha}$$

U_R: reference velocity
Z_R: reference height
α: power coefficient

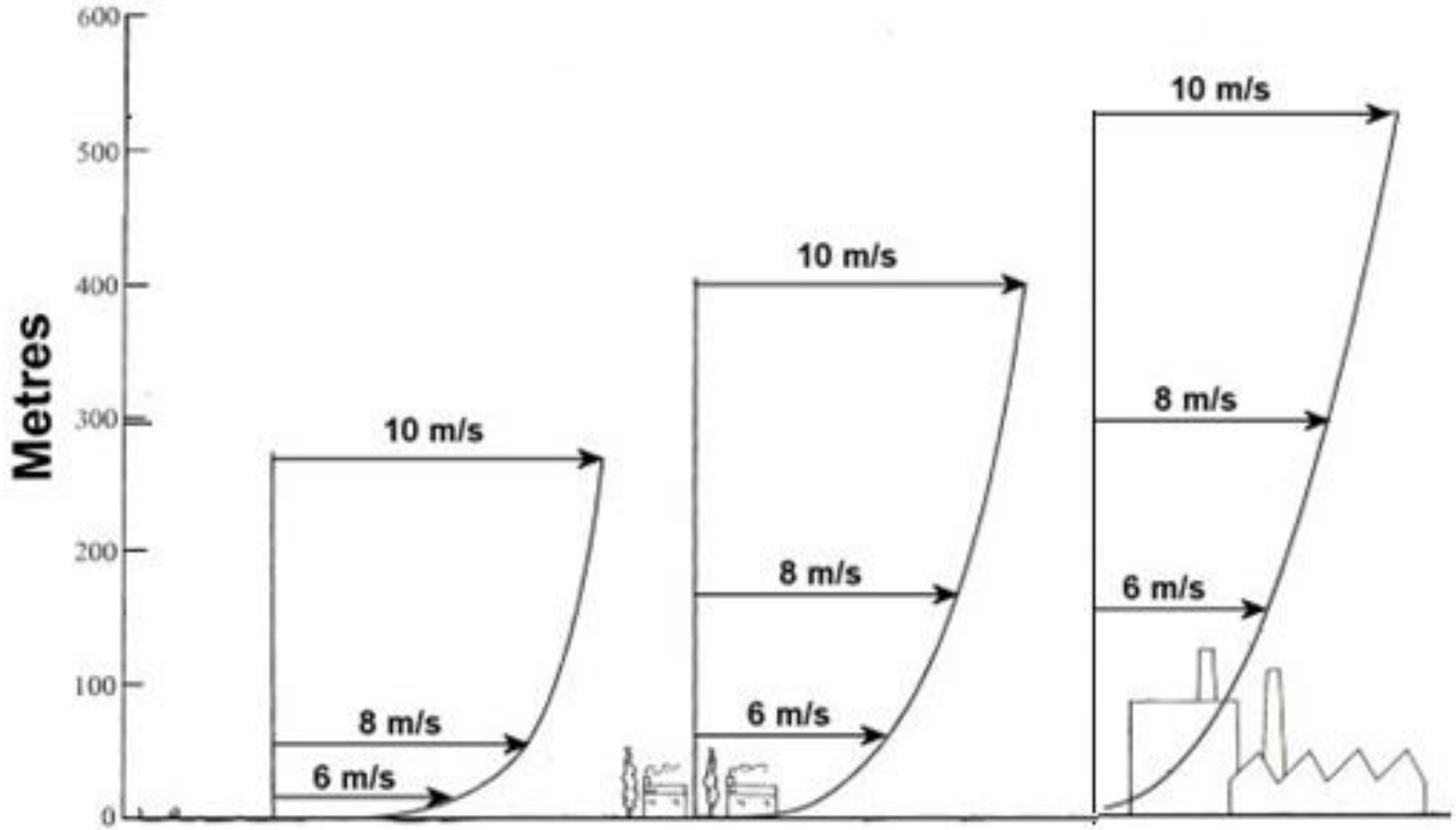
Boundary conditions reproduction

- Velocity profile

Roughness class	Slightly rough (0)	Moderately rough (I and II)	Rough (III)	Very rough (IV)
Type of terrain	Ice, snow, water surface	Grassland, farmland	Park, suburban area	Forest, inner city area
Z_0 (VDI)	10^{-5} to $5\ 10^{-3}$	$5\ 10^{-3}$ to 0.1	0.1 to 0.5	0.5 to 2
Z_0 (ESDU)	10^{-3} to $3\ 10^{-3}$	$10^{-2}\ 3\ 10^{-2}$	0.1 to 0.3	> 0.7
Z_0 (Eurocode)	$3\ 10^{-3}$	10^{-2} to $5\ 10^{-2}$	0.3	1
α (VDI)	0.08 to 0.12	0.12 to 0.18	0.18 to 0.24	0.24 to 0.4

Boundary conditions reproduction

- Velocity profile



Boundary conditions reproduction

- Velocity profile

  – logarithmic law:

  (derived from NS,
  valid in the surface layer)

$$\frac{\overline{U(z)}}{u^*} = \frac{1}{\kappa}\ln\left(\frac{z-d}{z_0}\right)$$

displacement in case of rough conditions

U: mean velocity
z: height
u*: friction velocity
z_0 aerodynamics roughness length
d: displacement height
κ: von Karman constant

  – power law:

  (engineering approach,
  valid for all the ABL)

$$\frac{\overline{U(z)}}{U_R} = \left(\frac{z-d}{z_R-d}\right)^{\alpha}$$

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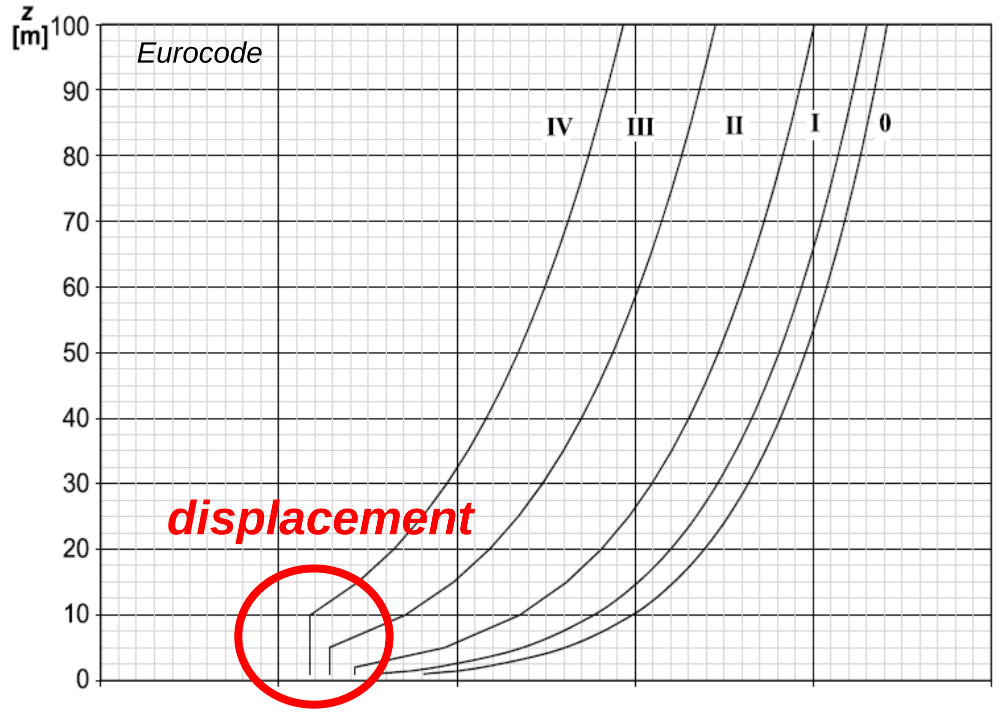
Boundary conditions reproduction

- Velocity profile



Roughness class	Slightly rough (0)	Moderately rough (I and II)	Rough (III)	Very rough (IV)
Type of terrain	Ice, snow, water surface	Grassland, farmland	Park, suburban area	Forest, inner city area
d (VDI)	0	0	0.75 h	0.75 h
d (ESDU)	0	0	5 to 10	15 to 25
d (Eurocode)	1	2	5	10

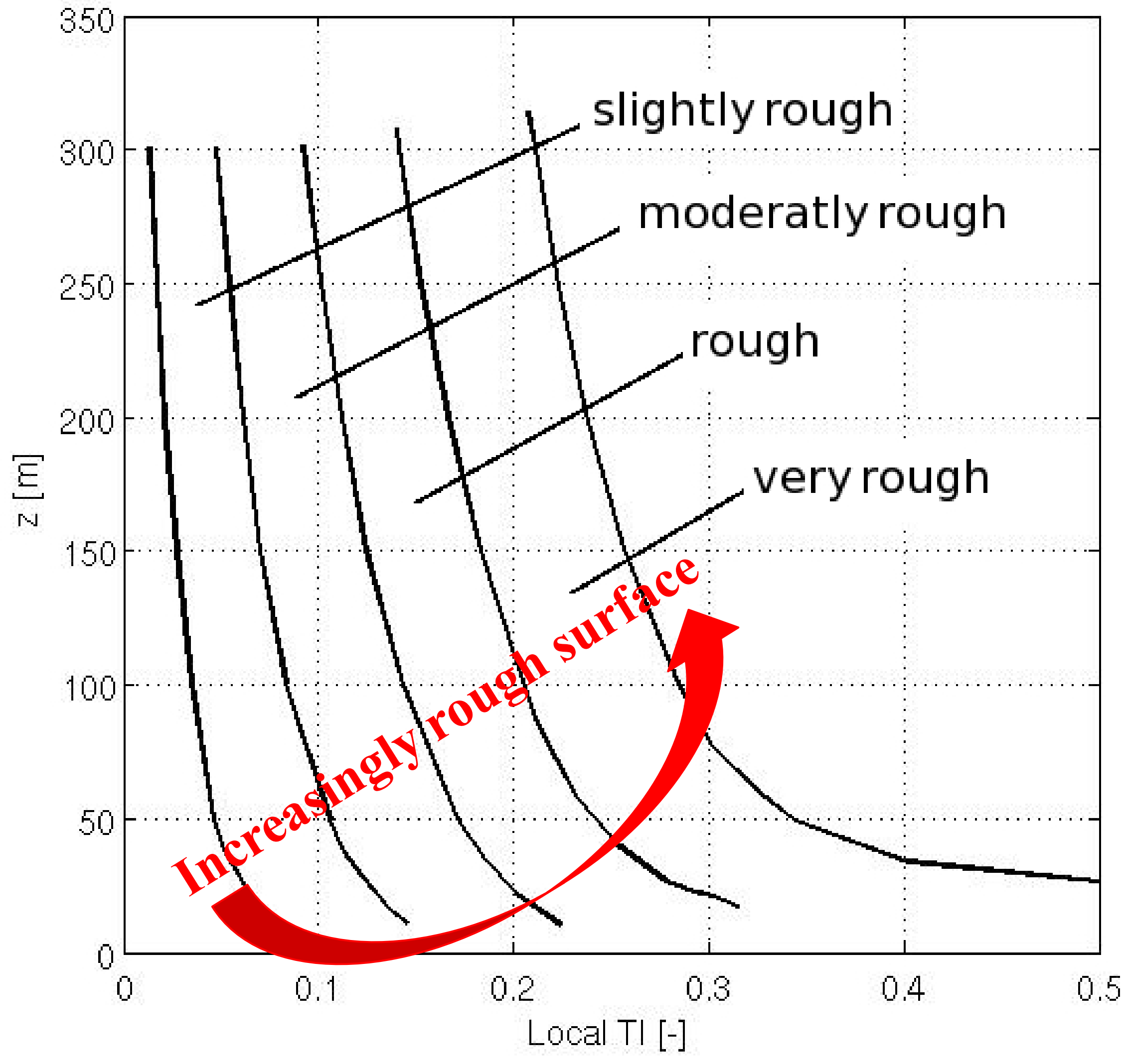
Boundary conditions reproduction

- Turbulence profile
  (turbulence level)

  – terrain roughness is also associated to specific turbulence properties

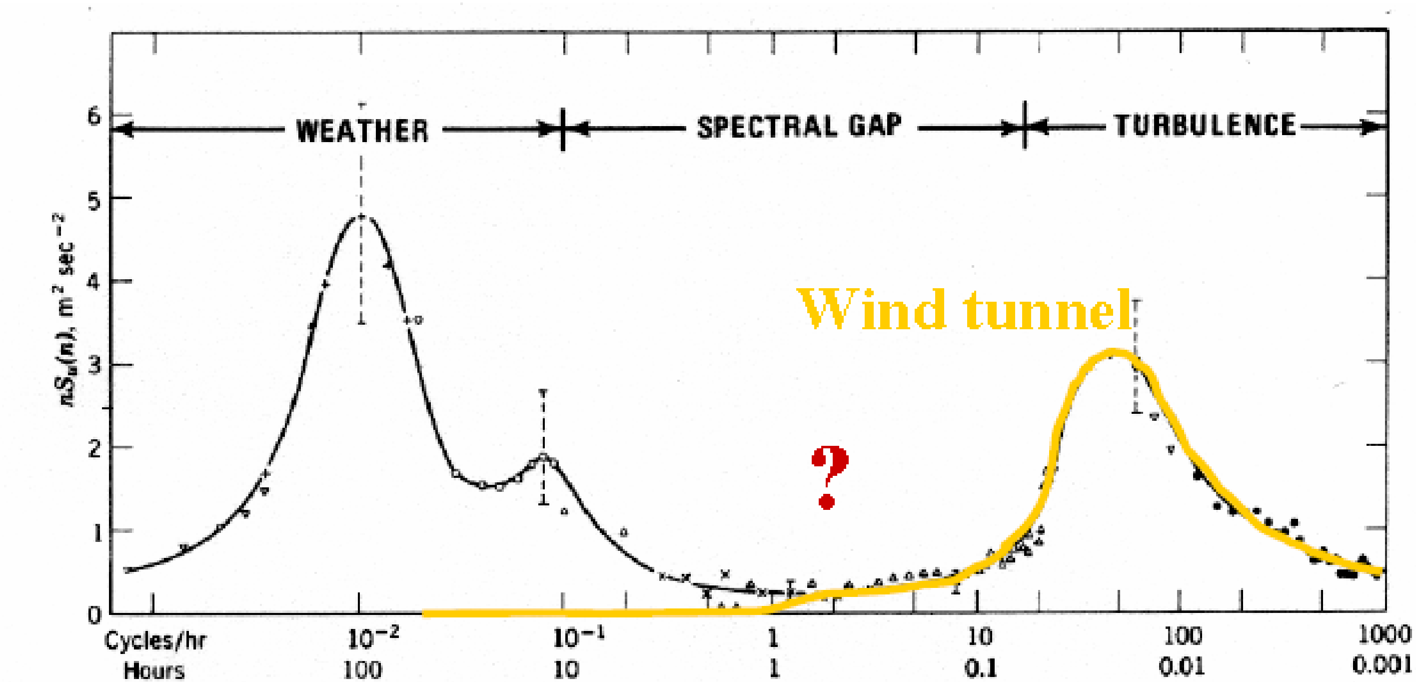
  – norms exist for the three wind velocity directions !!

  → but this is not enough…



Boundary conditions reproduction

- Wind speed fluctuation spectra
  - Von der Hoven (57)



→ constant weather conditions

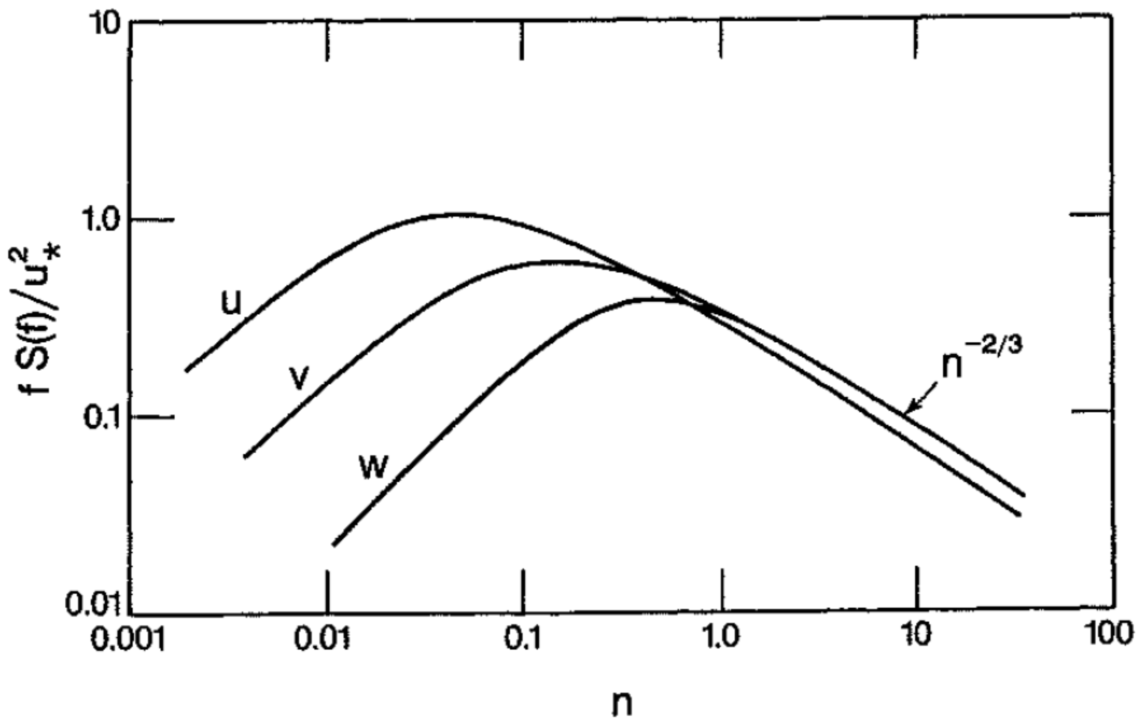
Boundary conditions reproduction

- Turbulence spectra
  - turbulent kinetic energy distribution
    - normalized spectra for u, v and w in a neutral surface layer over a flat terrain described by Kaimal (1972)

$$\frac{fS_{uu}(f)}{u_*^2} = \frac{102n}{(1+33n)^{5/3}}$$

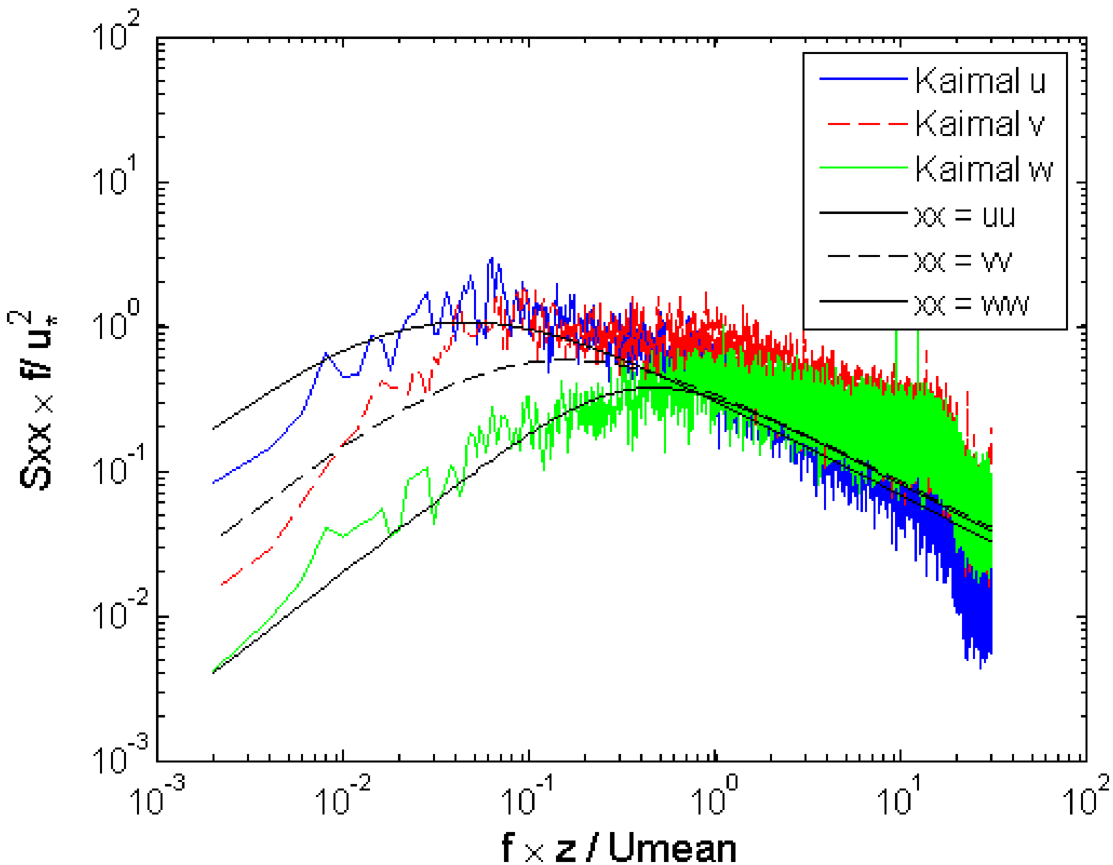
$$\frac{fS_{vv}(f)}{u_*^2} = \frac{17n}{(1+9.5n)^{5/3}}$$

$$\frac{fS_{ww}(f)}{u_*^2} = \frac{2.1n}{(1+5.3n^{5/3})}$$



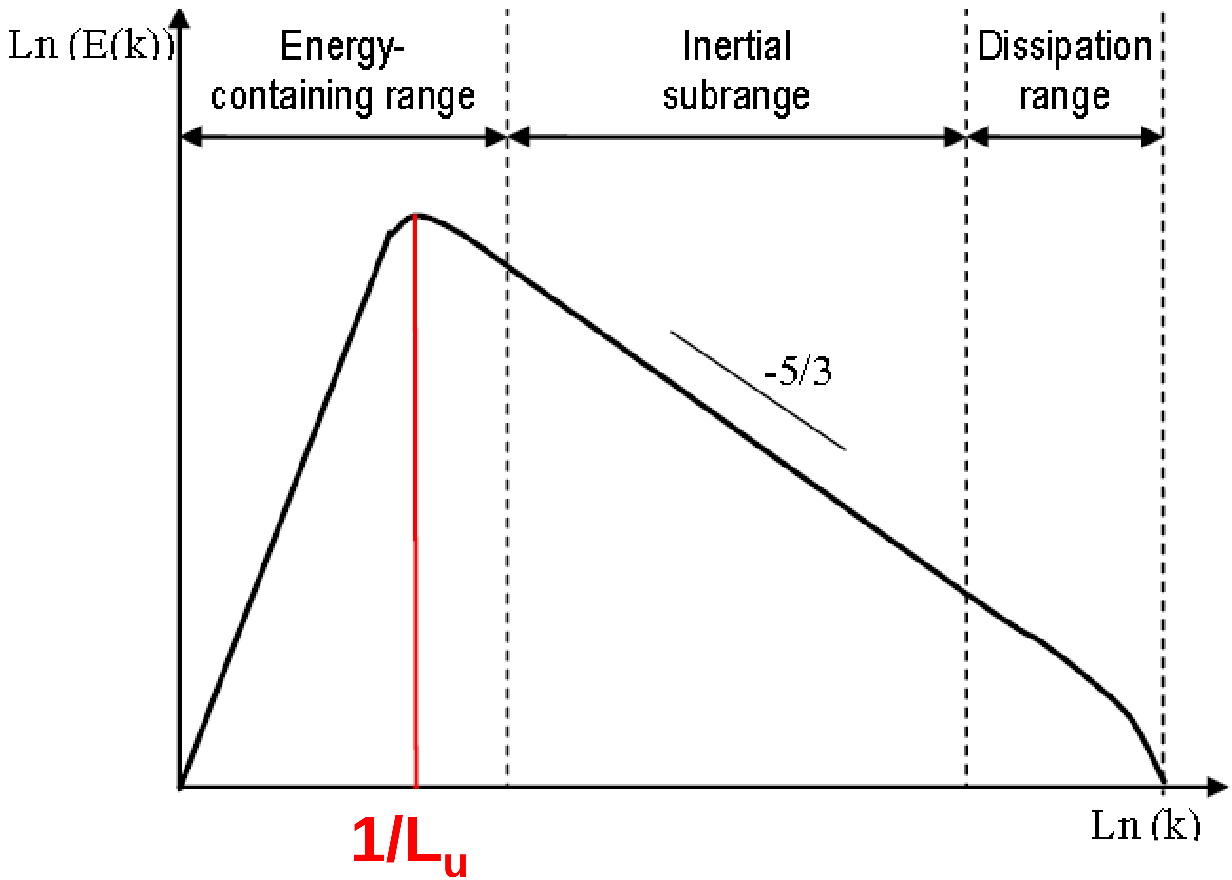
Boundary conditions reproduction

- Turbulence spectra
  - example of wind tunnel measurements:



Boundary conditions reproduction

- Turbulence length scale profile
  - $L_{X,U}(Z)$ is the most energetic turbulent scale

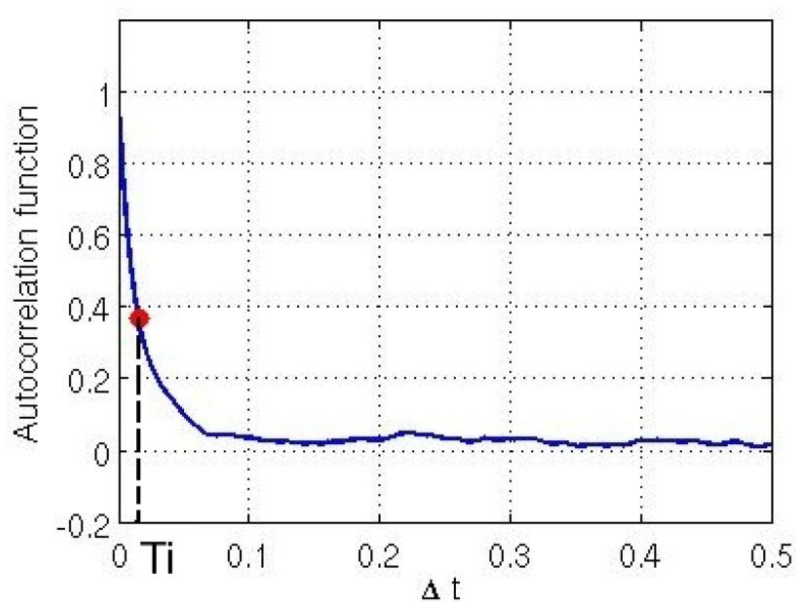


Boundary conditions reproduction

- Turbulence length scale profile
  - in practice, from a time signal

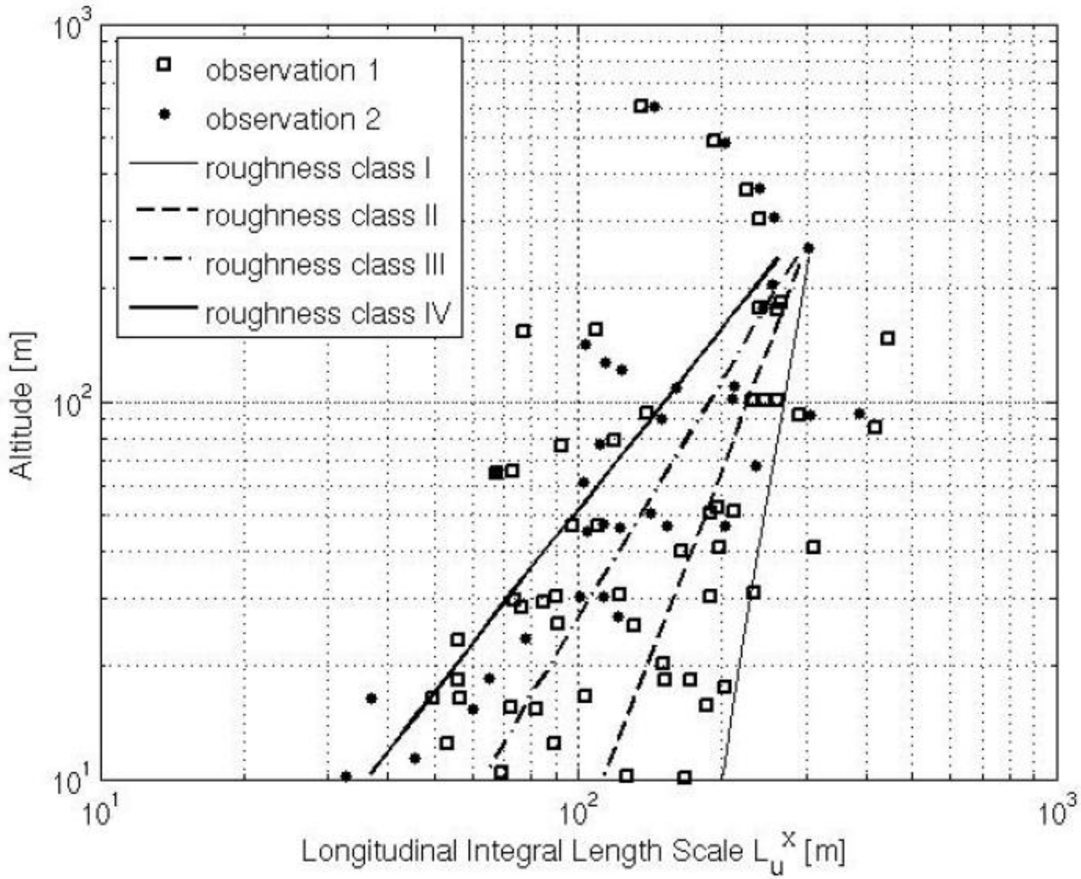
    →integral time: integral of the autocorrelation. (1/e or zero-crossing technique can be used)

    →Lu is recovered with Taylor frozen turbulence hypothesis and the mean wind s



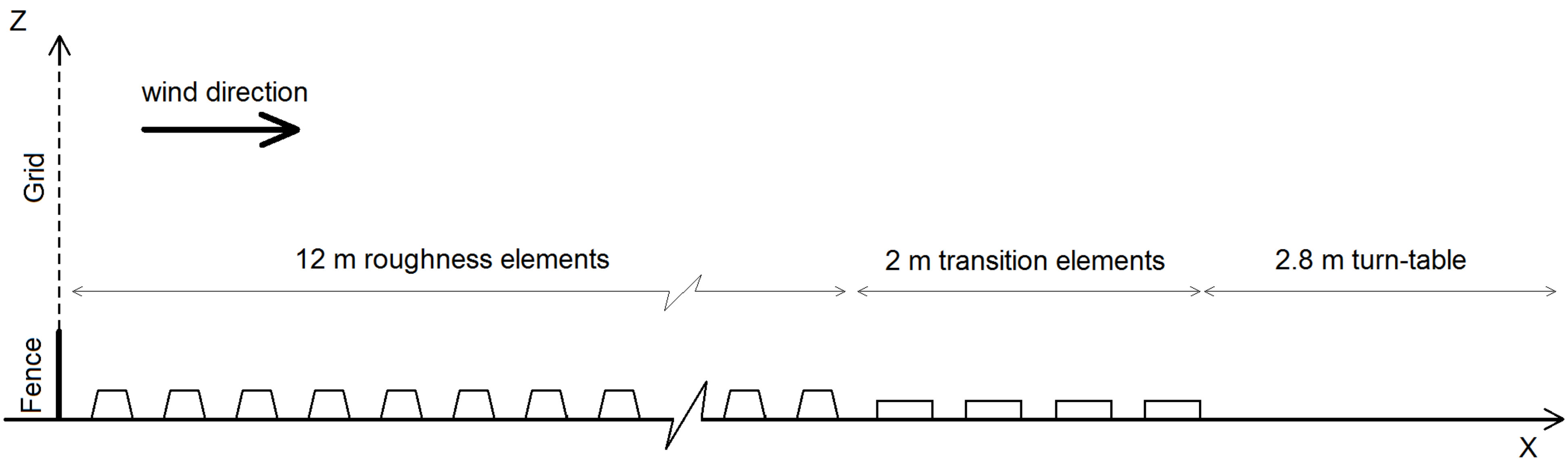
Boundary conditions reproduction

- Turbulence length scale profile
  - Lu vertical profile depends on the terrain roughness: Counihan (75)



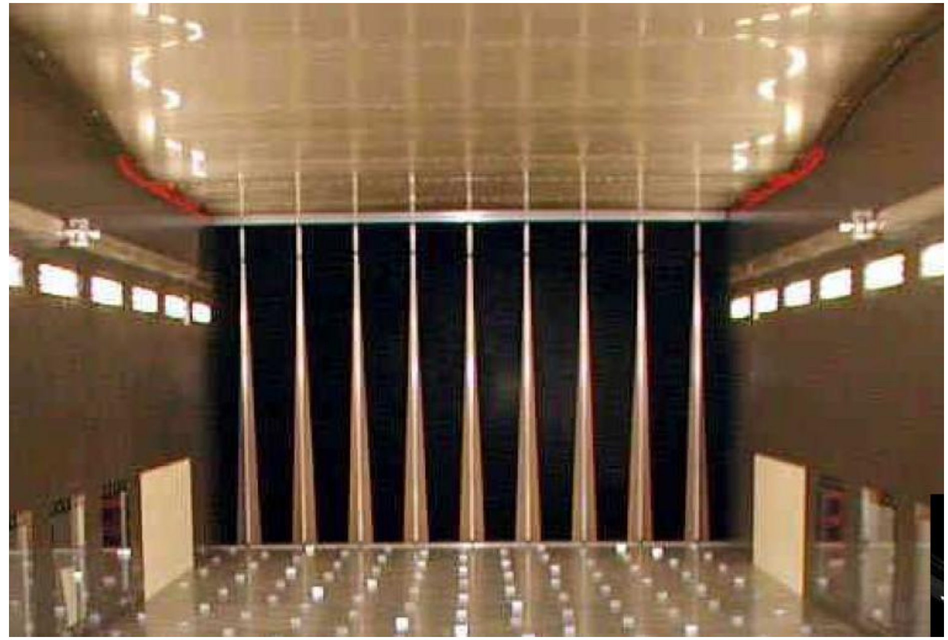
Boundary conditions reproduction

- Other requirements
  - fully development state
  - zero longitudinal pressure gradient
- In practice
  - grid, fence, Counihan wings, roughness elements

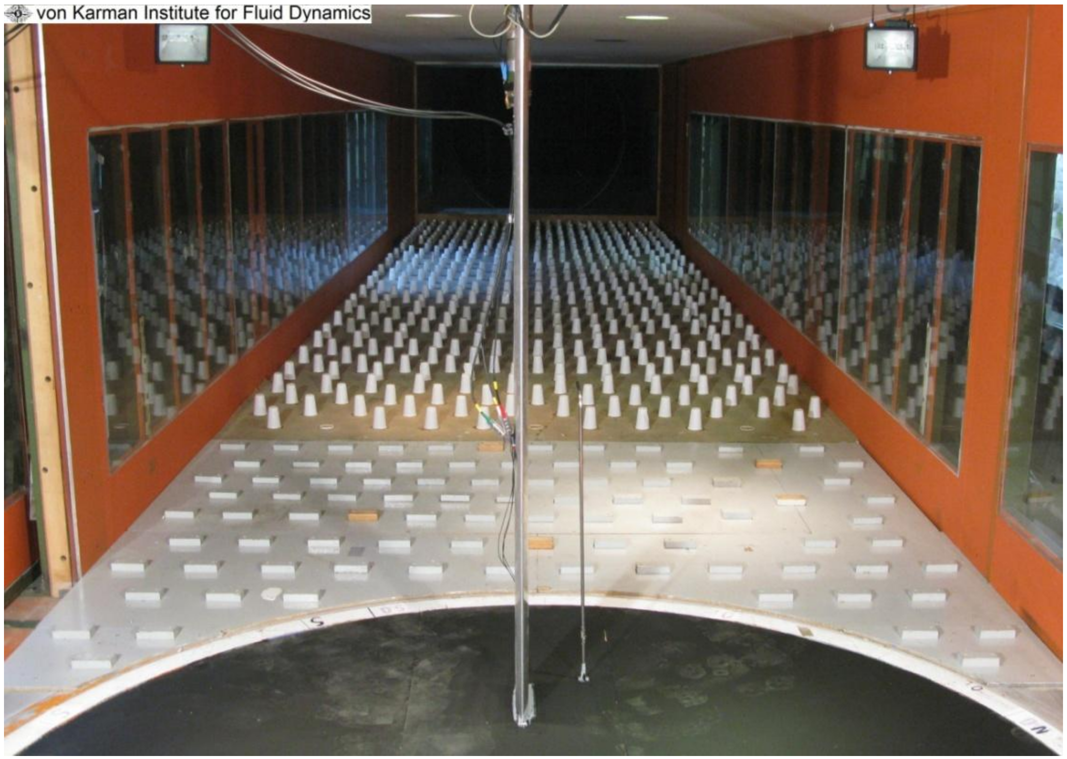


Boundary conditions reproduction

- Example



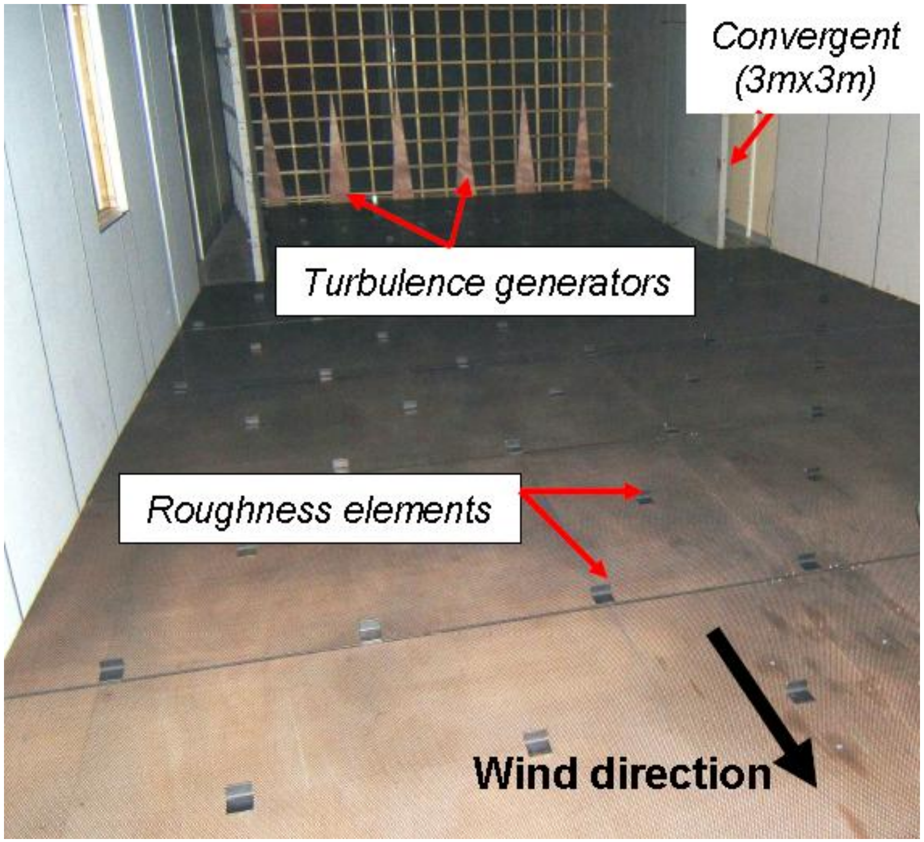
WOTAN University of Hamburg, Ge



VKI-L1, von Karman Institute, Be

Boundary conditions reproduction

- Example

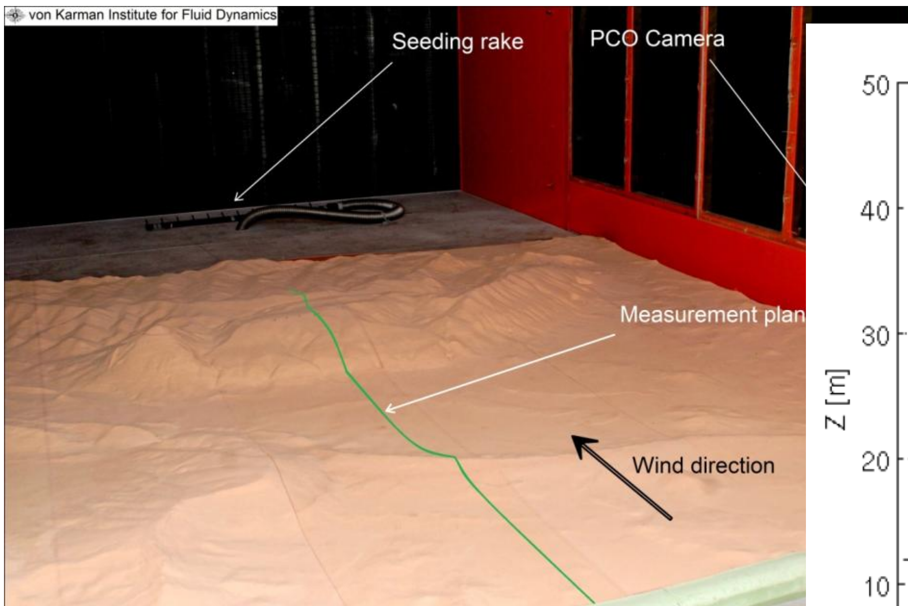


Malavard, university of Orléans, Fr

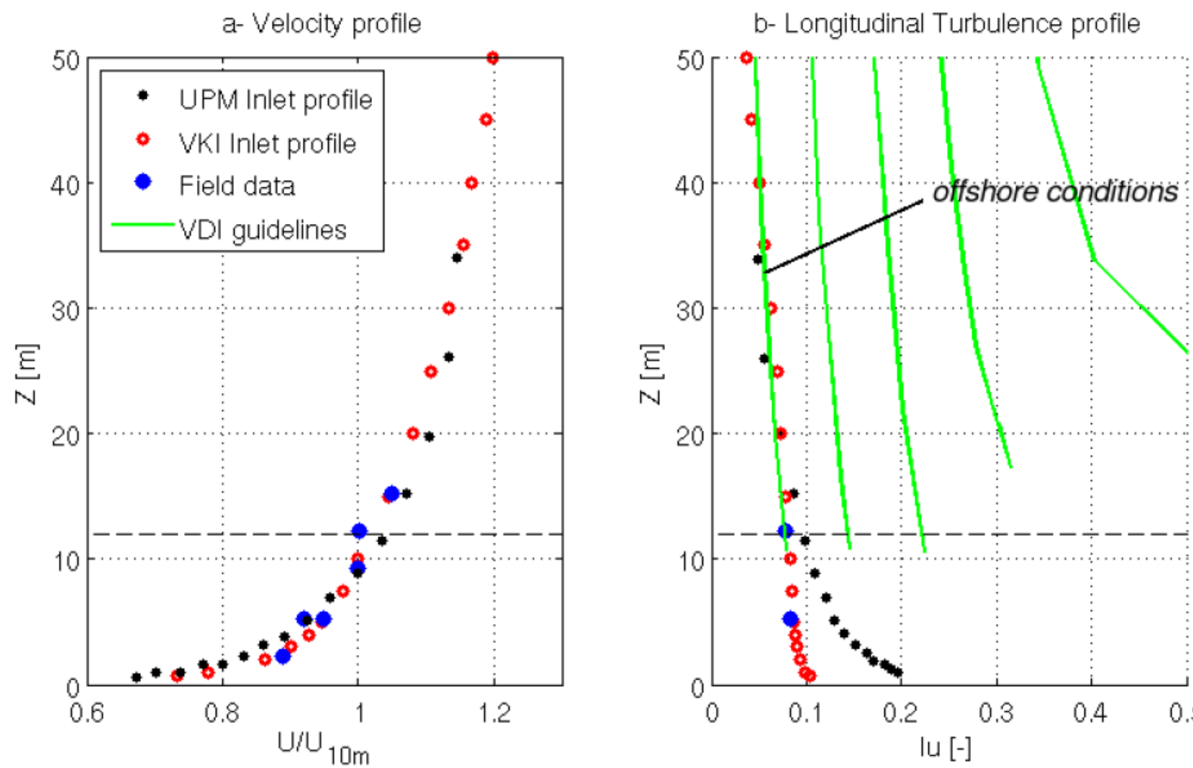
Ecole Centrale de Nantes, Fr

Applications

- Complex topographies
  - Bolund hill, 1/500 scale
  - Alaiz mountain, 1/5000 scale

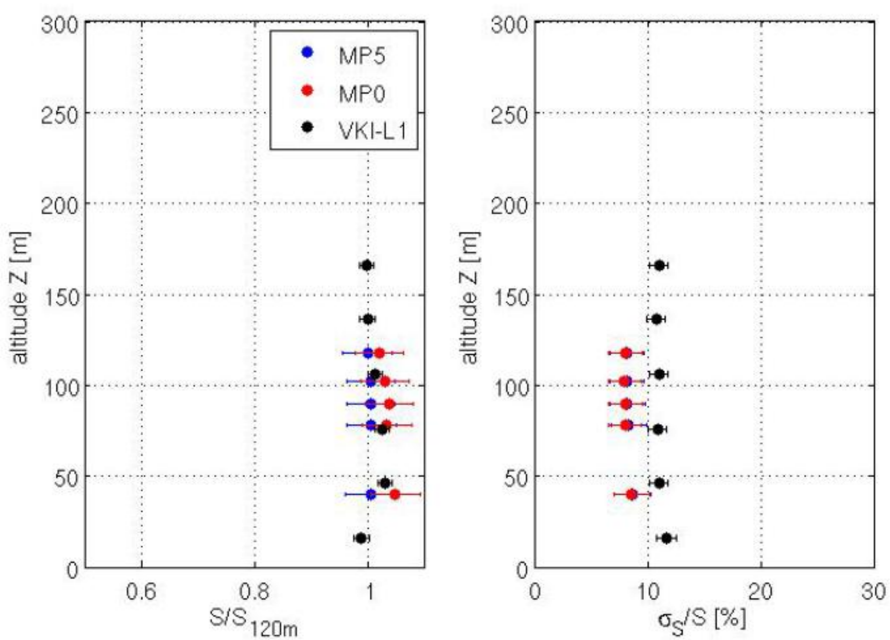


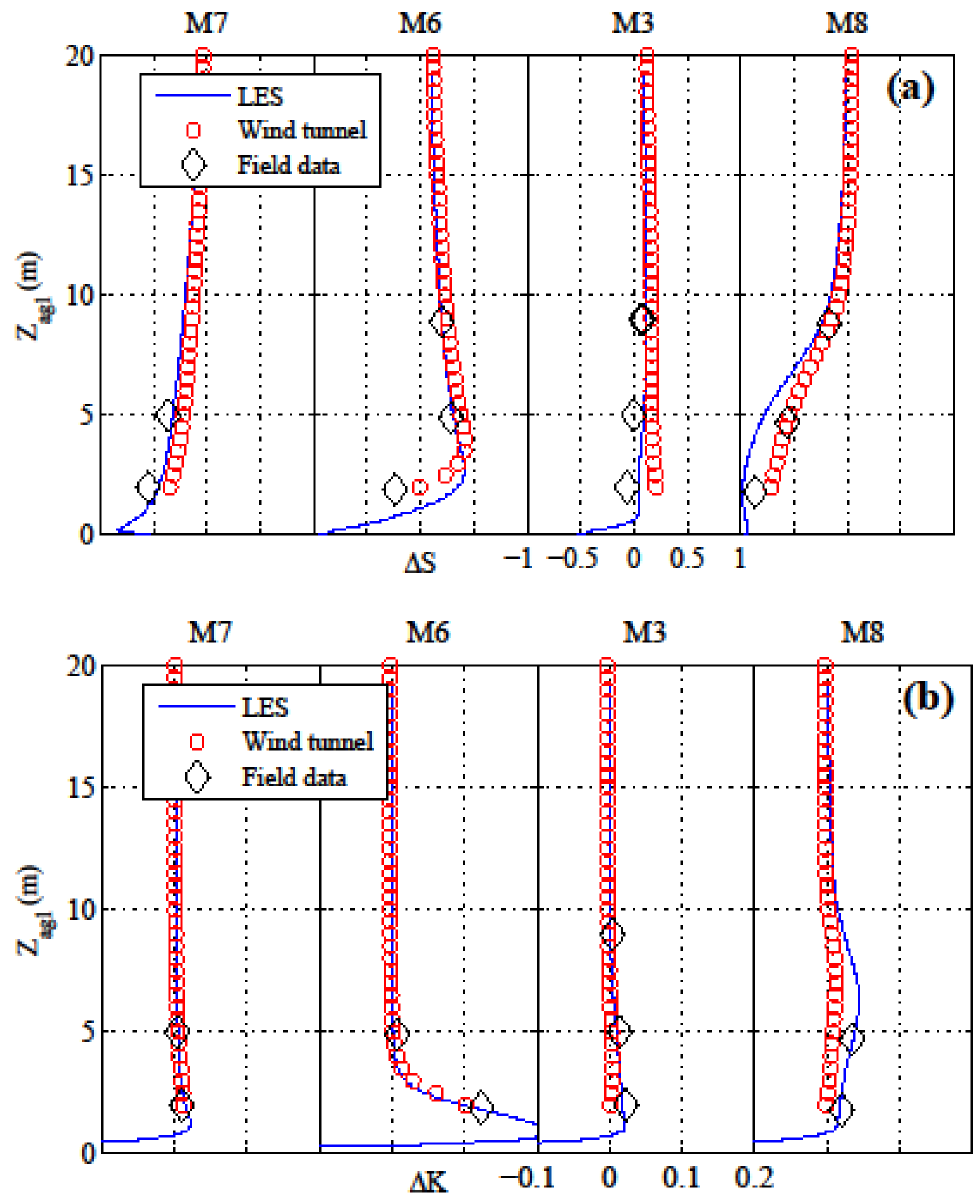
Von Karman Institute for fluid dynamics, BE



Applications

- Complex topographies
  - Bolund hill, 1/500 scale
  - Alaiz mountain, 1/5000 scale





Applications

- Forest area
  - porous media
  - dense solid cylinders

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Applications

- Urban area
  - real
  - idealized

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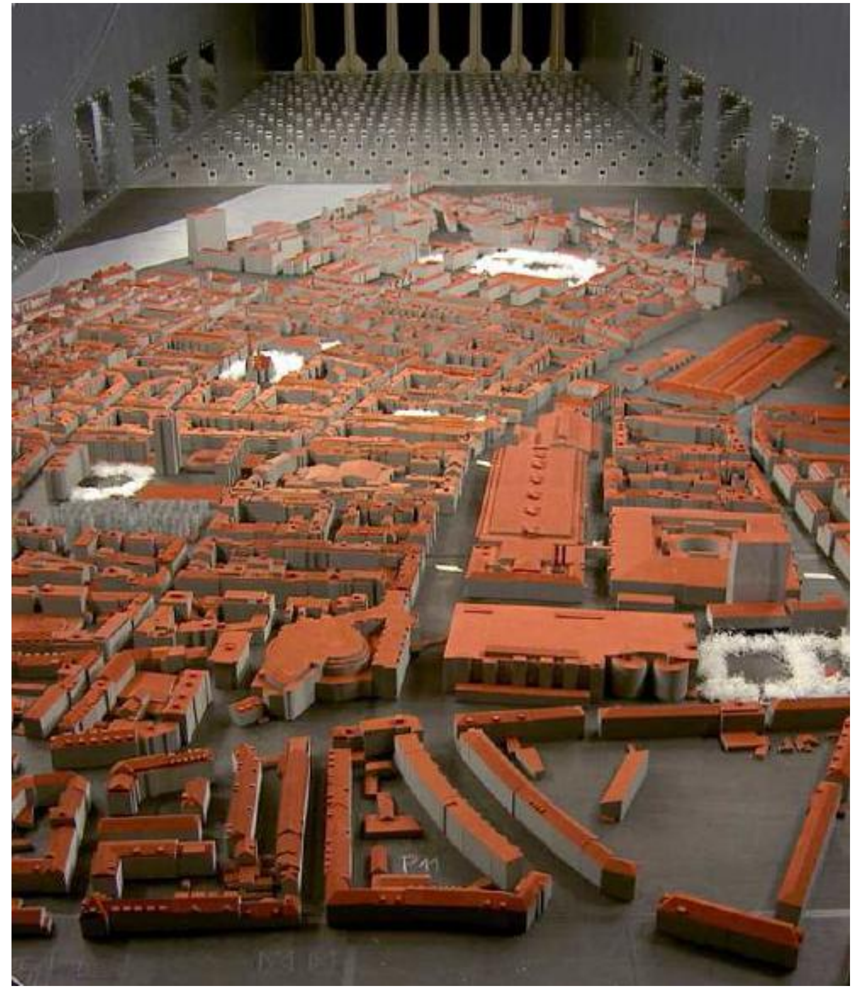

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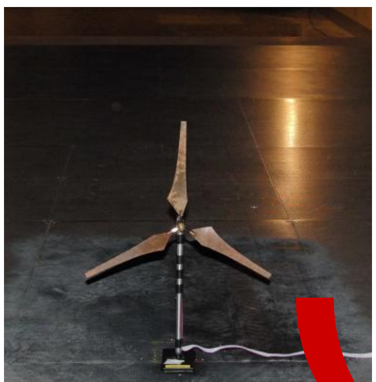
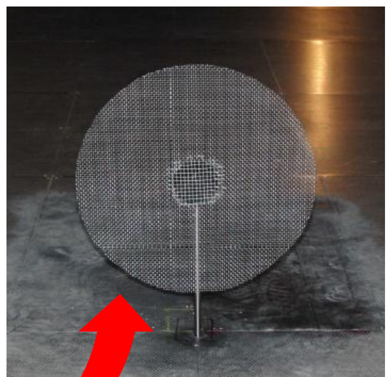
Applications

- Wind turbine simulation
  - spinning model
  - porous media





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Thank you for your attention

Some references:

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