**Fachtagung “Lasermethoden in der Strömungsmesstechnik”**
8. – 10. September 2015, Dresden

# Introduction of a new forest model for wind-tunnel studies and PIV-measurements of flow phenomena at the windward forest edge

## Vorstellung eines neuen Wald-Modells für Windkanaluntersuchungen und PIV-Messungen von Strömungsphänomenen an der luvseitigen Waldkante

**Christof Gromke*, Bodo Ruck**
Laboratory of Building- and Environmental Aerodynamics, Institute for Hydromechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
*gromke@kit.edu

Key words: similarity, vegetation, forest edge, atmospheric boundary-layer, PIV
Schlagworte: Ähnlichkeit, Vegetation, Waldkante, atmosphärische Grenzschicht, PIV

### Abstract

The Reynolds number sensitivity of the flow past a reduced-scale forest model is investigated for simulated atmospheric boundary-layer flows with different gradient velocities. Focus is on the analysis of the mean streamwise velocity field in the windward forest edge region. The vertical profiles of the normalized mean streamwise velocity do not reveal qualitative differences between the various Reynolds number flows. However, quantitative differences up to 75% are observed within the inflection layer. They continuously increase in downstream direction. As an explanation, the concept of two basic wake type structures, a large-scale and a small-scale wake, which superimpose, is introduced. The small-scale wake gains relevance relative to the large-scale wake in downstream direction. The lower limit Reynolds number above which the flow can be considered Reynolds number insensitive is suggested to be a function of the streamwise distance from the windward forest edge.

### Introduction

Flow phenomena and wind forces at forest edges are of particular relevance for forest stand stability. Observations after storm events suggest a particularly high risk of wind-induced forest damage near stand edges. A complex interaction of atmospheric flow and permeable forest edge lead to a vertical momentum input, which can cause tree failure shortly behind the edge. Once started in the edge-near region, windthrow spreads into the forest stand and destroys subsequent trees, which are more vulnerable than edge trees due to poorer growing conditions. Raupach et al. 1996 and Finnigan 2000 compared the flow over the forest edge with a plane mixing layer and suggested that Kelvin-Helmholtz instabilities lead to coherent structures, which are responsible for a damaging vertical momentum input and which, apparently, have been identified in the field by Gao et al. 1989. However, the relation between coherent structures and tree failure in forests remained far from clear as stated in Schütz et al. 2006. Tischmacher and Ruck 2013 gained more insight into the corresponding flow behaviour by wind-tunnel experiments with forest edge models, artificially generated 3D wind gusts and TR-PIV measurements. They pointed out that experimental as well as numerical simulations carried out in the past did not account for severe gusts, which are most likely responsible for the initial damage. The latter is due to the fact that by simulating only an input velocity profile, neither in experimental nor in numerical simulations, severe vertical momen-

tum input can be modelled. Furthermore, Tischmacher and Ruck 2013 could show that the interaction of discrete severe gusts with forest edges leads to the formation of a strong primary vortex due to a cross flow phenomenon, which enhances the intrusion of high speed momentum from the gust into the edge-near canopy. Phenomenologically, the formation of the primary vortex differs from the predictions of existing theories, which attribute the vortex formation to a pure Kelvin-Helmholtz instability.
In order to continue the investigations and study the flow phenomena in the upstream forest edge region under controlled and appropriate flow conditions, a novel small-scale wind-tunnel forest model was developed and subjected to a simulated atmospheric boundary-layer flow. In this paper, the novel forest model is introduced. Before performing discrete gust simulations, the similarity of the atmospheric background flow should be guaranteed with the new forest model. Thus, the similarity requirements essential for the transferability from small-scale to the full-scale are discussed. First results of Particle Image Velocimetry (PIV) flow field measurements for approach boundary-layer flows with different gradient velocities are presented and the sensitivity of the flow field in the forest edge region on the approach flow Reynolds number is analyzed.

## Experiment Setup and Measurement Technique

### *Simulated atmospheric boundary-layer approach flows*

The measurements were performed in the open working section of a closed-circuit Goettingen-type wind-tunnel. Windward of the working section, in the fetch, spires and ground-mounted roughness elements were installed to generate simulated atmospheric boundary-layer approach flows. Atmospheric boundary-layer approach flows with 9 different gradient velocities $U_\delta$ were simulated in order to investigate the Reynolds number sensitivity of the flows past the wind-tunnel forest model. Further details on the simulated approach flows are provided in Table 1, with $U_h$ the approach flow velocity at forest model top h = 0.115 m and $Re_h = U_h h/v$, where v is the kinematic viscosity of air, $v = 1.5*10^{-5}\ m^2 s^{-1}$. The aerodynamic roughness lengths $z_0$ of the approach flows were estimated to $z_0$ = 0.0014 m (± 0.0001 m). Assuming an agricultural used land area with mature crops ($z_0$ = 0.1 … 0.3 m) windward of the forest as it is typical for Central Europe, the geometric model scale M is determined to M = 1:200 (Wieringa 1993, WTG-Merkblatt 1995, Engineering Science Data Unit 2001).

| exp. no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| $U_\delta$ [m/s] | 1.0 | 2.0 | 4.0 | 6.0 | 8.0 | 10.0 | 12.0 | 15.0 | 20.0 |
| $U_h$ [m/s] | 0.5 | 1.0 | 2.1 | 3.2 | 4.2 | 5.4 | 6.7 | 8.3 | 10.3 |
| $Re_h$ [-] | 3,700 | 7,300 | 16,100 | 24,100 | 32,300 | 41,000 | 51,500 | 63,600 | 79,300 |

Table 1: Approach flow characteristics.

### *Forest model and similarity considerations*

In order to allow for the transferability of the measurement data obtained at a reduced-scale wind-tunnel forest model to full-scale conditions, the absorption of momentum from the air flow by the forest is considered as the relevant similarity criterion. To this end, the forest model was designed to consist of two horizontal layers with different flow resistances representing the stem and crown zone (Figure 1). In the stem layer, the primary sink for momentum is the form drag due to tree stems. They are modeled by ribbed cylindrical wooden dowels arranged in a staggered array such that the frontal-area index (projected windward facing area per unit ground area) geometrically scales to those of a typical forest stand. In the crown layer, the momentum absorption is due to form and viscous drag at the branches and leaves. The accumulation of branches and leaves is modeled by fibers packed together to form a permeable isotropic porous medium. Here, a scaling law based on the pressure loss coefficient which involves momentum absorption due to viscous and form drag is deployed to ensure similarity. This forest model design concept allows easily for a modification of the stem to crown layer momentum absorption ratio. Depending on the layer characteristics, momentum absorption ratios are estimated to lie between 1:10 and 1:5 for typical forest stands.

For the present study a forest with a full-scale tree stand density of $\rho_t$ = 1000 trees per hectare with an average tree stem of diameter $d_t$ = 0.30 m, height below crown $h_{tbc}$ = 8 m and drag coefficient $c_d$ = 1.2 (cylinder) was modeled. Since the momentum absorption per unit ground area in the stem layer is given by the product of the dynamic pressure ($p_{dyn} = 1/2\ \rho_{air}\ U^2$) with the drag coefficient $c_d$ and with the tree stem frontal area index ($d_t\ h_{tbc}\ \rho_t$), the following criterion for similarity is formulated according to

$$\left[p_{dyn}\ c_d\ \left(d_t\ h_{tbc}\ \rho_t\right)\right]_{fs} = \left[p_{dyn}\ c_d\ \left(d_t\ h_{tbc}\ \rho_t\right)\right]_{ms}\ M^2 \qquad (1)$$

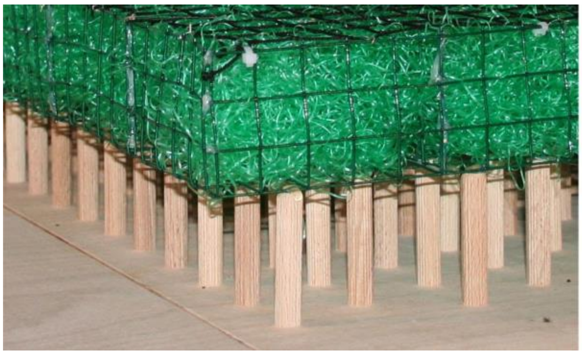
where the subscripts *fs* and *ms* stand for full-scale and model-scale, respectively. Under the premise / requirement that $c_{d,fs} = c_{d,ms}$ and $p_{dyn,fs} = p_{dyn,ms}$, equation (1) facilitates to

$$\left[\ d_t\ h_{tbc}\ \rho_t\right]_{fs} = \left[d_t\ h_{tbc}\ \rho_t\right]_{ms}\ M^2\ . \qquad (2)$$

For manufacturing purposes of the forest model it was preferable not to mimic each single tree stem. Hence, wooden dowels of 10 mm diameter corresponding to oversized full-scale tree stem diameters of 2 m were used. By reducing the tree stand density $\rho_{t,ms}$ in the forest model accordingly, an equivalent full-scale tree stand density $\rho_{t,fs}$ of 1,000 trees per hectare was realized.

In order to model the aerodynamic characteristics of the forest crown layer, a defined mass of fiber material was packed in to a defined volume to form a permeable isotropic porous medium. Here, a scaling law based on the pressure loss coefficient $\lambda$ [$m^{-1}$] which is a measure for the momentum absorption due to viscous and form drag is deployed to ensure similarity. The reader is referred to Gromke 2011 and Gromke and Ruck 2012 for a detailed description of the modeling approach and its underlying scaling and similarity laws.

For the forest model in this study, a fiber material packing density of 0.022 g $cm^{-3}$ was realized and the pressure loss coefficient was determined to $\lambda_{ms}$ = 120 $m^{-1}$. This corresponds to a full-scale pressure loss coefficient $\lambda_{fs} = \lambda_{ms} * M$ = 0.6 $m^{-1}$ and is, according to Grunert et al. 1984, who measured values for $\lambda_{fs}$ ranging from 0.53 $m^{-1}$ to 1.33 $m^{-1}$, a typical value for vegetation canopies.



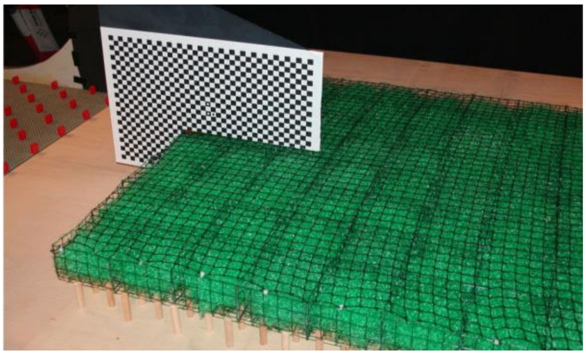


Figure 1: Wind-tunnel forest model.

*Particle Image Velocimetry (PIV) system and measurement*

A 2D/2C TR PIV system from Dantec Dynamics was deployed for the measurements. The system consisted of a high-speed CMOS sensor with 1,280 x 800 pixel resolution and a pulsed dual-cavity, frequency-doubled Nd:YAG laser, see Dantec Dynamics 2013 and Tischmacher and Ruck 2013 for more details. Recordings were made in the streamwise-oriented spanwise-central vertical plane (x-z) covering the forest edge region from $x^+ = x/h = -1.5$ to $x^+ = +3.5$, with h the tree height (Figure 2).
The double-frame, single-exposure mode was employed with an inter-frame rate of 0.25 Hz to ensure the recording of independent velocity field snapshots where the intra-frame times were varied between 120 and 2,400 ns depending on the approach flow velocity to record 1,000 double-frames during an experiment. The recordings were evaluated with Dynamic-Studio from Dantec Dynamics using a 2-step adaptive correlation algorithm with final interrogation window size of 32 x 32 pixel by 50% overlap along both dimensions (Dantec Dynamics 2013).

## Results and Discussion

Figure 2 shows vertical profiles of the normalized mean streamwise velocity $U(z)^+ = U(z)/U_h$ for a total of 11 $x^+$-position in front of, at and behind the forest edge. For the purpose of clearness, only profiles of selected Reynolds number flows $Re_h$ are shown, namely of the two lowest Reynolds number flows ($Re_h$ = 3,700 and $Re_h$ = 7,300), a medium Reynolds number flow ($Re_h$ = 32,300) and the highest Reynolds number flow ($Re_h$ = 79,300), corresponding to experiment numbers 1, 2, 5 and 9, respectively, see Table 1.

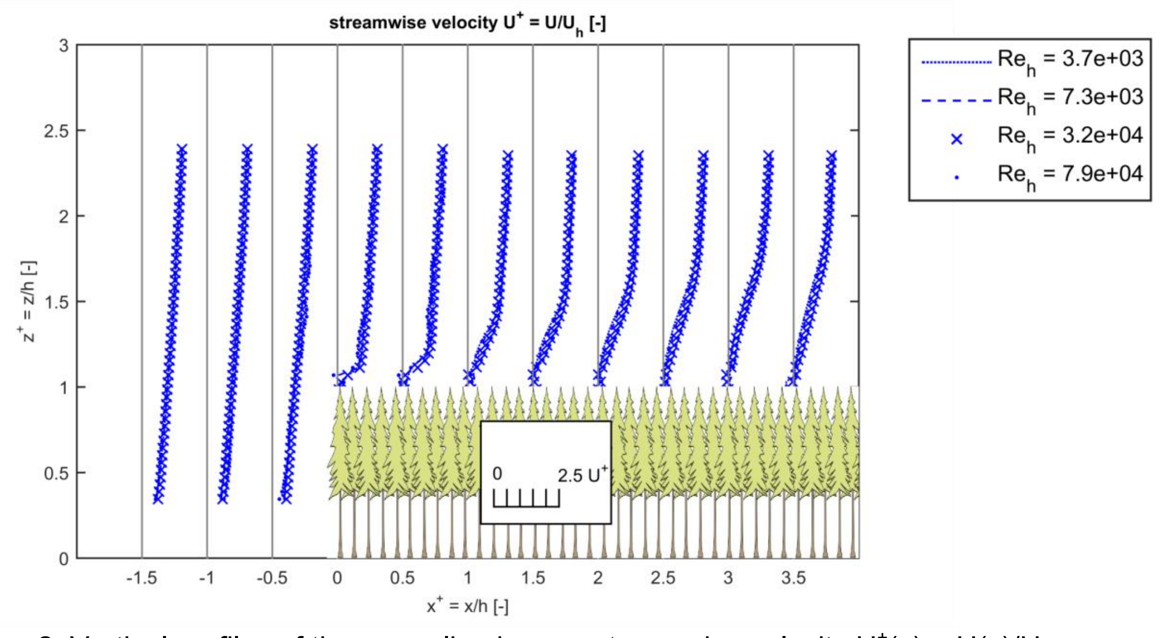



Figure 2: Vertical profiles of the normalized mean streamwise velocity $U^+(z) = U(z)/U_h$.

Figure 2 allows for a qualitative comparison between the various Reynolds number flows. As can be seen, the normalized profiles $U^+(z)$ collapse into confined bands at each streamwise position $x^+$. The bands are broadest above the forest canopy ($x^+ > 0.0$), generally in the height-level $1.0 < z^+ < 1.5$. Above $z^+ = 1.5$, the widths of the profile bands are comparable to those of the approach flow profiles in front of the forest edge, $x^+ < 0.0$. The layer directly above the forest canopy top shows inflected velocity profiles with large gradients. With increasing z-position, the velocity gradients increase below the inflection point and decrease

above. It is hence referred to as inflection layer. Its depth increase in streamwise direction and is of comparable magnitude for all Reynolds number flows.
However, no characteristic differences between the profiles belonging to different Reynolds number flows are apparent. In order to quantify the differences, a specific measure, the relative normalized difference (RND) is introduced. The relative normalized difference rel($\Delta\Phi^+$) is defined according to

$$\mathrm{rel}(\Delta\Phi^+) = \frac{\Phi^+_{Re_{h,x}} - \Phi^+_{79,300}}{\Phi^+_{79,300}} \cdot 100 \quad [\%] \tag{3}$$

where $\Phi$ = U in the case of the mean streamwise velocity. The differences are expressed in percent [%] and are related to the flow with the maximum Reynolds number ($Re_h$ = 79,300) since this flow is considered to be the most Reynolds number independent one among the realized flows.
The relative normalized differences rel($\Delta U^+$) for the mean streamwise velocities of all Reynolds number flows are provided in Figure 3. In the approach flows, $x^+ < 0.0$, the relative normalized differences are generally smaller than 5%, and hence they are considered to be Reynolds number insensitive. The slight increases in rel($\Delta U^+$) towards the windward forest edge are attributed to an upstream flow disturbance caused by the overpressure which builds up in front of the forest canopy. Starting from the forest edge, the relative normalized differences become continuously larger in downstream direction and attain values of up to 75% directly above the forest canopy top. However, they are restricted to the inflection layer which increases in depth with downstream distance. Above the inflection layer, the relative normalized differences are comparable in magnitude to those in the approach flow. To understand this phenomenon, the flow field downwind of the forest windward edge is conceptionally thought to be formed by the superposition of two basic wake types resulting from the separation of flows of different velocity scales at elements of different length scales, a large-scale wake (lsw) and a small-scale wake (ssw), respectively. The large-scale wake arises from flow separation at the forest windward edge, i.e. the separation causing elements and the largest wake structures are of tree model height h, and the velocity is of the magnitude of the approach flow velocity at tree height $U_h$. The small-scale wake originates from the low-velocity flow around the smallest tree model elements which are fibers with a couple of hundred micrometer diameter, see Figure 1. Whereas for the large-scale wake type Townsend's *Reynolds Number Similarity Hypothesis* applies (Townsend 1956), i.e. the Reynolds numbers ($Re_{lsw} \approx Re_h$) are sufficiently high to allow for turbulent flows which are structurally similar despite being dynamically not similar, the small-scale wake type Reynolds numbers are little ($Re_{ssw}$ < few hundreds or even $Re_{ssw}$ < few tens) and they do not show structural similarity. For these low Reynolds numbers, the element drag coefficient is not constant but approximately inversely proportional to the Reynolds number and consequently the small-scale wake is Reynolds number sensitive. The continuous increase in the relative normalized differences rel($\Delta U^+$), and hence an increase in Reynolds number sensitivity, is due to the growing relevance of the small-scale wake over the large-scale wake with downstream distance from the windward forest edge.
The question whether or not there is a lower limit Reynolds number $Re_{ll}$ above which the flow past the forest model can be considered as Reynolds number insensitive, and if so - what is its value, can not be answered in a definite global sense. The answer rather involves a lower limit Reynolds number which is a function of the streamwise distance $x^+$ from the windward forest edge, i.e. $Re_{ll}(x^+)$.

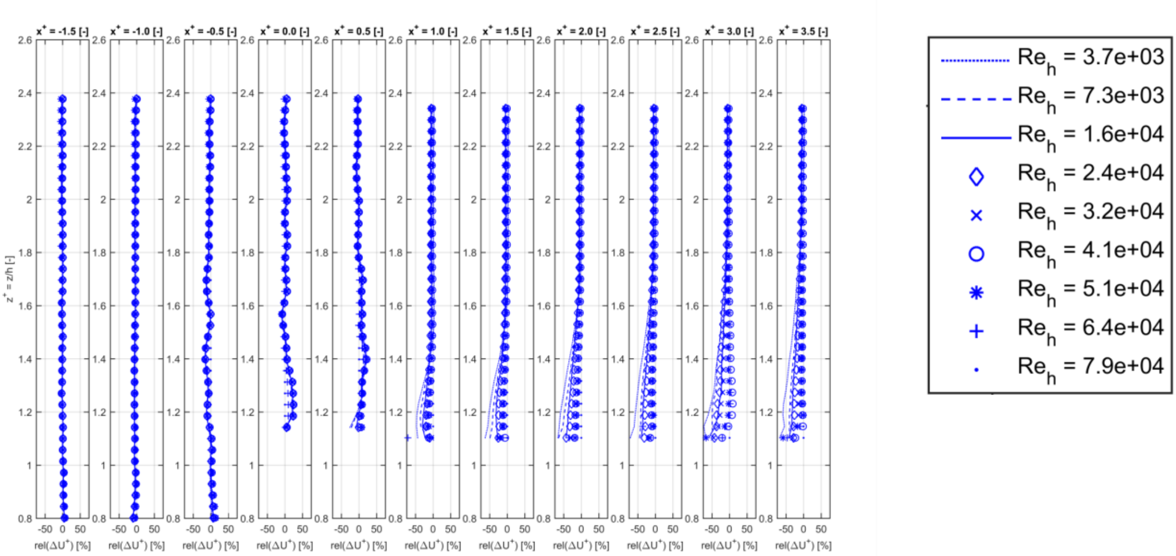



Figure 3: Relative normalized differences rel(ΔU$^+$) of the mean streamwise velocities.

## Summary and Conclusions

A novel reduced-scale wind-tunnel model for studying forest flows was developed. The scaling and similarity laws distinguish between the stem and the crown layer. Based on these laws, it was shown that the realized forest model adequately represents the momentum absorption in a full-scale forest. Measurements of the flow field in the windward forest edge region were performed with Particle Image Velocimetry (PIV). The focus of the investigation was the Reynolds number sensitivity of the flow past the forest model for simulated atmospheric boundary-layers with same profile shape (identical aerodynamic roughness length $z_0$) but different gradient velocities $U_\delta$. For approach flow boundary layers spanning a one-order-of-magnitude range in gradient velocity Reynolds number, the mean streamwise velocity fields were analyzed. In the vertical profiles of the normalized mean streamwise velocity $U^+(z)$, see Figure 2, no qualitative differences between the different Reynolds number flows were observed. The normalized profiles collapsed into confined bands which were broadest in the inflection layer directly above the forest canopy. On top of the inflection layer, the widths of the profile bands were comparable to those of the approach flow profiles in front of the forest. The relative normalized difference (RND), see equation (3), was introduced as a measure to quantify the variation among the different Reynolds number flows. They revealed larger differences of the mean streamwise velocities within the inflection layer, ranging up to 75%, see Figure 3. The differences increased in streamwise direction with distance from the windward forest edge. This was explained by the concept of superposition of two basic wake types resulting from the separation of flows with different velocity scale at elements of different length scale, a so called large-scale wake (lsw) and a small-scale wake (ssw), where the small-scale wake becomes more relevant relative to the large-scale wake with increasing distance from the forest edge. Finally, it was concluded that the lower limit Reynolds number $Re_{ll}$ above which the flow can be considered Reynolds number insensitive is a function of the streamwise distance from the windward forest edge.


## Acknowledgement

The financial support of the Deutsche Forschungsgemeinschaft DFG (German Research Foundation) under grant no. Ru 345/30-2 is gratefully acknowledged by the authors.

## References


Dantec Dynamics, 2013: “DynamicStudio User’s Guide”, Version 3.40, pp.1-660

Engineering Science Data Unit, 2001: “Characteristics of atmospheric turbulence near the ground - Part II”, ESDU 85020, pp. 1-42

Finnigan, J., 2000: “Turbulence in plant canopies“, Annual Review of Fluid Mechanics, Vol. 32, pp. 519-571

Gao, W., Shaw, R.H., Paw U, K.T., 1989: “Observation of organized structure in turbulent flow within and above a forest canopy”, Boundary-Layer Meteorology, Vol. 47, pp. 349-377

Gromke, C., 2011: “A vegetation modeling concept for Building and Environmental Aerodynamics wind tunnel tests and its application in pollutant dispersion studies”, Environmental Pollution, Vol. 159, pp. 2094-2099

Gromke, C., Ruck, B., 2012: “Pollutant concentrations in street canyons of different aspect ratio with avenues of trees for various wind directions”, Boundary-Layer Meteorology, Vol. 144, pp. 41-64

Grunert, F., Benndorf, D., Klingbeil, K., 1984: “Neuere Ergebnisse zum Aufbau von Schutzpflanzungen“, Beiträge für die Forstwissenschaft, Vol. 18, pp 108-115

Raupach, M.R., Finnigan, J.J., Brunet, Y., 1996: “Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy”, Boundary-Layer Meteorology, Vol. 78, pp. 351-382

Schütz, J.P., Götz, M., Schmid, W., Mandallaz, D., 2006: “Vulnerability of spruce (Picea abies) and beech (Fagus sylvatica) forest stands to storms and consequences for silviculture”, European Journal of Forest Research, Vol. 125, pp. 291-302

Tischmacher, M., Ruck, B., 2013: “Interaction of gusts and forest edges an experimental wind-tunnel study”, Forestry, Vol. 86, pp. 523-532

Townsend, A.A., 1956: “The Structure of Turbulent Shear Flow”, Cambridge University Press, pp. 1-315

Wieringa, J., 1993: “Representative Roughness Parameters for Homogeneous Terrain”, Boundary-Layer Meteorology, Vol. 63, pp. 323-363

WTG-Merkblatt, 1995: “Windkanalversuche in der Gebäudeaerodynamik“, Windtechnologische Gesellschaft, pp. 1-43