Comparison of Different Measurement Techniques and a CFD Simulation in Complex Terrain

‡Christoph Schulz, ‡Martin Hofsäß, ‡Jan Anger, ‡Alexander Rautenberg, ‡Thorsten Lutz, ‡Po–Wen Cheng and ‡Jens Bange

‡Institute of Aerodynamics and Gas Dynamics (IAG) University of Stuttgart, Pfaffenwaldring 21, 70569 Stuttgart, Germany
‡Stuttgart Wind Energy @ Insitute of Aircraft Design (SWE), University of Stuttgart, Allmandring 5b, 70569 Stuttgart, Germany
♭Environmental Physics, University of Tübingen, Hölderlinstr. 12, 72076 Tübingen, Germany
E-mail: ‡schulz,lutz@iag.uni-stuttgart.de

Abstract. This paper deals with a comparison of data collected by measurements and a simulation for a complex terrain test site in southern Germany. Lidar, met mast, unmanned aerial vehicle (UAV) measurements of wind speed and direction and Computational Fluid Dynamics (CFD) data are compared to each other. The site is characterised regarding its flow features and the suitability for a wind turbine test field. A Delayed–Detached–Eddy–Simulation (DES) was employed using measurement data to generate generic turbulent inflow. A good agreement of the wind profiles between the different approaches was reached. The terrain slope leads to a speed–up, a change of turbulence intensity as well as to flow angle variations.

1. Introduction

Without doubt the importance of wind energy has increased stepwise in the last decades. In 2015 wind power overtook hydro and is now the third largest source of energy in Europe with a share of 15.6% on total power production [1]. During this process complex terrain sites stepped more into focus. This means according to Huschke [2] sites featuring strong changes in orography as well as in topography or more generalised hilly and mountainous terrain [3]. A good classification is given by Wegeley et al. [4] and Hiester & Pennell [5]. Wegeley et al. [4] define a terrain as flat if the elevation differences between the turbine site and the terrain are below 60 m within a 3 km radius of the turbine site and the maximum grade in this region is below 3%. An additional criterion by Hiester & Pennell [5] is the difference between the elevation of the hub and the lowest elevation within 5 km upstream of the site, which should be greater than three times the elevation difference within the same distance (Figure 1). If one criterion is not fulfilled a terrain is considered to be complex. The use of wind turbines in these environments increases the complexity of wind park planning processes. Orography influences, among other things, the boundary layer profile and turbulence characteristics of the flow [6–8]. Several studies on these topics have been performed in recent years. One of the well–known investigations is the study by Bowen and Lindley [7], who examined the influence of different escarpments on the wind speed and turbulence in wind tunnel tests. Emeis et al. [8] studied measurement data of an escarpment in Denmark and found direct relations between spectra and terrain amongst others. Further investigations providing a large database for comparisons have emerged from...
the Askervein [9] and Bolund experiment [10]. A lot of investigations has been performed on the Bolund hill like the one of Jafair et al. [11] using an immersed boundary method. In contrast to this, Prospathopoulos et al. [12] used a body-fitted grid as it is done in this article. Even though a lot of other wind tunnel experiments are available in literature dealing with the topic, it is out of the scope of this article to mention all of them. In general, the existing data are often not taken at full-scale level complex terrain sites. The Bolund peninsula for example is usually described as a scaled down wind turbine site and also the studies of Emeis et al. [8] took only a 20 m high escarpment into consideration. In these cases, scalability plays a role and cannot be neglected at all points of interest. Some of these are the impacts of atmospheric stability and Coriolis force which gain importance in larger scale terrain. A further discussion is given by Berg et al. [10] It is therefore of interest to study the behaviour of the flow at a full scale site and to get information about the flow without considering scaling effects as it has e.g. done by Brodeur & Masson [13] for a complex terrain site in Canada. Another motivation for the presented examinations is the fact that complex terrain flows are not well understood. Many of the prediction tools used for wind turbine and wind farm planning are not able to capture the complex flow situations which accompany with complex sites [14, 15]. One of the results can be the reduction of financial benefit because of differences between estimation models and real events occurring at the site [16]. An example for this is the Windpark Nordschwarzwald located in southern Germany for which the annual wind speed differs about 25% from the estimated one [17]. Those incorrect plannings lead, besides financial loss, to negative public perception. For future wind parks in complex environments planning mistakes have to be avoided.

The investigations presented show results of measurements and a simulation of a complex terrain site in southern Germany close to the town of Stötten. The main goals of the study are to increase the understanding of complex terrain flows and to determine a suitable area for a later wind turbine test site. Secondly, a comparison of different measurement techniques and a numerical simulation shall be made. As measurement techniques a lidar system [18], a met mast and an unmanned aerial vehicle (UAV) were used. UAVs are besides lidar and met masts getting more common for wind turbine related applications in flat as well as in complex terrain. In this context the work of Reuder et al. [19, 20] and their colleagues as well as the work at ETH Zürich [21–23] and in the US e.g. by Barthelmie et al. [24] shall be mentioned. The numerical simulation for this study was performed at the IAG\textsuperscript{1} using the flow solver FLOWer [25, 26]. This approach differs from usual mesoscale simulations with codes like the Weather Research and Forecasting Model (WRF) [27, 28] or PALM (Parallelized LES Model) [29]. Compared to mesoscale simulations a higher resolution and a smaller region were chosen as the future plan of the authors is to include a fully meshed wind turbine in the simulation and to perform studies on its aerodynamic behaviour in the given surroundings. Moreover, the small-scale turbulence should be maintained and studied investigating spectra and statistics.

The article will describe the main characteristics of the test site before a closer look at the measurement techniques and the numerical setup is taken. In the results section a comparison of the approaches based on different evaluation parameter will be shown and finally a recommendation regarding the suitability for a future wind turbine test site will be made.

\textsuperscript{1} Institute of Aerodynamics and Gas Dynamics of the University of Stuttgart
2. Test Site Characterisation
The test site examined is located close to Stötten in Baden-Württemberg, southern Germany. It is currently analysed in several German projects dealing with the improvement of complex terrain predictions numerically and based on measurements. Moreover, it is planned to build new met masts and test wind turbines in the area. One central feature of the site is the steep escarpment with maximum grades over 30% which can be seen in Figure 2 (left) at the west side of a flat plateau. Following the criteria defined above, the terrain can be considered as complex. The difference in height over the escarpment is up to 235 m. The plateau following the escarpment looking from West to East shows only small changes in height. In difference to the escarpment the plateau is nearly un-forested, having different fields for farm use. Figure 2 (right) shows the wind rose determined at the met mast positioned in the area at the GPS coordinates N48°39′49″ E9°50′49″. The met mast data investigated cover a period of about one year. The main wind direction derived from the data is about 295°, as it can be seen in the wind rose.

Figure 2:
Left: Overview of the test area. Each dot represents one reference point in the measurement evaluations. UAV data white; met mast green and the different lidar positions orange. Simulation area edges as pink rectangle. The x-axis has been rotated in main wind direction (WNW) with the flow approaching from negative x-values.
Right: Wind rose determined at the met mast over one year as layover with a topographical map of the test area.

3. Data Acquisition
3.1. Lidar
All lidar data were recorded using the SWE-Scanner [18], a fast pulsed lidar wind scanner based on a Leosphere Windcube V1 system with an adapted scanner unit. This system was originally developed as nacelle mounted lidar, but modified for the studies to be used as a ground based wind profiler. It measured the wind speed and direction in five heights (50 m, 75 m, 100 m, 125 m and 150 m) above ground. The used trajectory for this campaign was a modified velocity azimuth display (VAD) with five points in a circle having a half opening angle2 of 15° and one vertical point in the center (Figure 3). All five outer points are evenly distributed on the circle and all points per measured height are on the same level. The duration time of the trajectory was about 7.6 s. A validation of the system was done against the met mast showing a good correlation of the horizontal wind velocity at 100 m (Figure 4). The correlation coefficient of $r^2 = 0.943$, an offset of 0.2378 m/s and a slope of 1.079 were determined from the data. For this correlation the lidar was positioned near M1 and 4932 10-minute samples were analysed. All

\[ \text{angle between the vertical axis and the laser beam} \]
samples were filtered to consider only data within a carrier-to-noise (CNR) ratio between -22 dB and 5 dB. A data availability of the 10 minute interval of about 95% was reached. Finally, the system was used at the different locations shown in Figure 2 (left).

3.2. Met Mast
About 1 km away from the escarpment a 100 m met mast is located collecting data since February 2015. It is equipped with four cup anemometers having an accuracy 1%, three 3d sonic anemometers with an accuracy of 1.5% as well as with pressure and temperature sensors. All data were recorded with a sampling rate of 20 Hz. Vane anemometers are located in 25 m, 50 m, 75 m and 92 m height and determine the wind direction with an accuracy of 1°. Cup anemometers are positioned in 10 m, 25 m and twice at 100 m height. Sonic anemometers are placed in 50 m, 75 m and 98 m height. The equipment is in accordance with IEC 61400.

3.3. UAV
Recently, the University of Tübingen developed a small UAV called MASC (Multi-purpose Airborne Sensor Carrier) [30]. MASC is a fixed wing aerial vehicle with an interchangeable wing and a weight of approximately 5 kg. The operational time is about half an hour to one hour. MASC uses various sensors to measure different thermodynamic scalars. The measurement equipment is able to capture wind and temperature fluctuations up to 30 Hz and humidity fluctuations up to 3 Hz. More details about the measurement equipment can be found in the publications of Wildmann et al. [30, 31].

4. Numerical Modelling
4.1. Flow Solver and Simulation
For the numerical simulation the flow solver FLOWer was used. It is a compressible finite-volume flow solver using block-structured grids and featuring a wide range of turbulence models [25]. FLOWer has been extended at the IAG in the last years to account for turbulent atmospheric boundary layers as well as for complex terrain [26, 32–34]. The simulation was executed as Detached Eddy Simulation with a Spalart–Allmaras turbulence model with Edwards modification [35]. As subgrid-scale-model in the LES area a Smagorinsky–model was employed. A number of 40 inner iterations per time step was chosen with a dual-time stepping method for temporal discretisation [36]. The physical time step was chosen to be 0.2 s. The calculation of the convective fluxes was done using a fifth order WENO (Weighted Essentially Non-Oscillatory) scheme in all regions [37, 38] of interest and a second order Jameson–Schmidt–Turkel method [39].

---

3 temperature sensor accuracy 1 K and barometer accuracy 1 hPa
in regions of minor interest. In pre-investigations on the numerical parameters and the grid similar setups showed good results [40]. In total eight minutes were simulated and the results of the last minute taken for evaluation and averaging. The computational resources needed are 3800 CPUs for seven days on Hazhel Hen of the High Performance Computing Centre Stuttgart.

4.2. Background Mesh

One main point of complex terrain simulations is meshing effort. Different approaches have been made to use cuboid background meshes and immersed boundary methods [11] to minimise this effort. For the presented studies a body-fitted grid should be used by still keeping meshing costs as little as possible, increasing meshing comfort and repeatability. To reach these goals, an automated program was developed generating a Cartesian background mesh of cuboid shape and deforming it afterwards according to the terrain surface. In order to save computational resources the mesh uses hanging grid nodes meaning stepwise grid coarsening [41]. In the area of interest, the middle of the domain, the mesh has a resolution of 1 m (Figure 5). This is kept constant over the whole x-direction. 300 m above ground and away from the x-axis the mesh starts to coarsen, still maintaining the general mean flow features but not the turbulent statistics. In areas of interest Pope’s criterion of \( \frac{k_{\text{sgs}}}{k_{\text{resolved}}} < 0.20 \) is fulfilled. Meaning the turbulent kinetic energy modelled by the subgrid scale-model is less than 20% of the total turbulent kinetic energy. This points at a sufficient grid resolution for the DES. Overall, the mesh created consists of about 150 million cells and covers about 6 km\(^2\). As boundary conditions a no-slip wall at the ground is employed and the inflow plane is defined to feed a constant atmospheric boundary layer profile into the simulation. No wall functions were used. The inlet velocity profile is equivalent to the one determined at the met mast. Further details will be given in the following section. All other boundary conditions are defined as far-field.

4.3. Inflow Data Generation

Based on the anemometer of the met mast different modelling parameters for the model of Mann [42] were derived. The model used was based on the von Karman spectrum and the rapid distortion theory to estimate shear effects. As input parameters for the model the length scale \( L \), the stretching factor \( \Gamma \) and the dissipation \( \alpha \varepsilon^{2b} \) were needed. The distribution of the energy in the spectrum is derived from \( L \) and \( \alpha \varepsilon^{2b} \), whereas \( \Gamma \) controls the shear. For the studies \( L \) was set to 65 m, \( \alpha \varepsilon^{2b} = 0.035 \) and \( \Gamma = 3.9 \). Performing an inverse Fourier Transformation the turbulent fluctuations were modelled using the Mann model spectrum \( C_{ij} \) and the Gaussian random complex variable \( n_j \):

\[
  u_i(x) = \sum_k e^{ikx} C_{ij}(k)n_j(k); i, j = 1, 2, 3
\]

Following the modelling approach a time signal of one minute duration was created having a turbulence intensity of 10%\(^4\), saved to files and read in later during the simulation. A longer signal as used in mesoscale simulations is not feasible as both the computational resources and the available disc storage were limited.

In the later simulation a mean wind profile following the power law having neutral stratification (\( \alpha = 0.14 \)) was imposed at the inlet boundary using a Dirichlet boundary condition. Further downstream a turbulence plane was placed to feed the turbulent fluctuations of the Mann box into the flow field. The values read from previously saved files were added up by a source term approach similar to Troldborg [43] to the flow field using the fluctuation vector \( \tilde{u} \), the

\(^{4}\) The turbulence intensity was determined at the met mast as well. According to Emeis et al. [8] the impact of the terrain should diminish drastically up to this position. A measurement further upstream was not possible because of legal issues.
grid spacing normal to the transverse plane $\Delta n$, the mean normal velocity $U_n$ and the normal fluctuation component $u_n$:

$$\tilde{f}_P = \rho \tilde{u} \cdot \left( U_n + \frac{1}{2} u_n \right)$$

(2)

The source terms created in this way are then smeared inside the flow field to avoid numerical oscillations. For this sake a Gaussian convolution is applied, with $n - n_d$ being the distance between the turbulence plane and the point in the flow field:

$$\tilde{f}_\epsilon = \tilde{f}_P \ast \eta_\epsilon, \eta_\epsilon(n) = \frac{1}{2\Delta n \sqrt{\pi}} \cdot exp \left[ - \left( \frac{n - n_d}{2\Delta n} \right)^2 \right]$$

(3)

5. Results

Figure 6 displays the comparison of the simulation and the measurements at different positions in the terrain. The corresponding measurement positions can be seen in Figure 2. Simulation and measurement show an increase of the velocity up to 150 m above ground directly at the edge of the escarpment ($M_4$). This is a consequence of the narrowing of the stream tube at the escarpment. Similar observations have been made by Bowen and Lindley [7] as well as by Emeis et al. [8] amongst others. The speed-up above $z_{ground} = 50$ m is about 1.2 for the simulation. It reduces 200 m downstream at $M_3$ to 1.1 and at the met mast position $M_1$ the wind profile is fully recovered. The agreement between lidar data and simulation is good at all measurement points. Regarding the UAV data larger deviations close to the escarpment at $M_4$ are apparent. At 100 m height the difference is about $0.2 \times u/u_{ref}$, whereas at other heights the agreement is significantly better. At $M_3$ similar trends can be noticed. Further downstream at $M_2$ and $M_1$ the data correlate well with lidar and simulation. One reason for the deviations in the results may be the different ways of data acquisition. Being extracted and averaged over 60 seconds the simulation data do not consider larger scale atmospheric influences. In contrast to this, the averaging time of the lidar system is 30 minutes and lies within the spectral gap proposed in literature [44, 45].

![Figure 6](image_url)

**Figure 6:** Normalised wind speed of measurements (lidar □; UAV △) and simulation (---) at different positions at the test site. Normalised speed in black and inclination angle in red.
divided in spatial sections (evaluation windows). The data in each of these sections is considered for the later averaging. For the data shown here, the average and the statistical quantities in these sections were determined over different flights. In general, an influence of for example changing atmospheric conditions between the data evaluated can not be completely denied, even though the data have been filtered regarding atmospheric stratification among others using the met mast signal. This may be a possible explanation for e.g. the zig–zag shape of the profile seen in Figure 6 for $M_4$ and $M_3$. Looking at the statistics, only values of flights of one measurement day are considered. This is done to avoid the impact of varying inflow speeds on different measurement days on the statistic values. Figure 7 shows these data in different heights above ground in comparison with the simulation as well as the corresponding normalised wind speeds. In the UAV and simulation data an increase of velocity can be seen in general following a similar trend and being in accordance with the findings in Figure 6. Prompting is the maximum of the speed–up being further upstream in 100 m height for the UAV than in the simulation. The maximum of the UAV data is about $u/u_{ref} = 1.3$ at $x = -1400$ m and the one of the simulation about $u/u_{ref} = 1.4$ at $x = -1000$ m. This effect is not visible 150 m above ground where both approaches show a similar slope with a maximum of about $u/u_{ref} = 1.3$ and a speed increase beginning at $x = -1500$ m. A possible influence on this can be the presence of the forest at the escarpment and the blockage caused by this which is not considered in the simulation. Regarding the normalised standard deviation of the time series larger differences are apparent. In the UAV data an increase of fluctuations up to a maximum of $1.3 \times \sigma_{ref}$ at the escarpment can be seen especially in 100 m above ground. In contrast to this the values decrease in the simulation to about $0.6 \times \sigma_{ref}$ which is in accordance with the results of e.g. Emeis et al. [8] and Bowen and Lindley [7]. With increasing height the trend in the simulation stays similar. More downstream the normalised standard deviation keeps constant as also observed by Imamura et al. [46] in their simulations. These findings are not reflected in the UAV data. The zig–zag spread of the data seen e.g. Figure 7 (right) indicates an influence of the evaluation procedure on the results. In future studies different flight paths and evaluation metrics are planned to deeper investigate into these phenomena.

Figure 7: Normalised standard deviation in red and normalised wind speed in black at $y = 0$ m in different heights above ground of the UAV measurements (▲) and the simulation (—). Velocities normalised by the reference velocity of the inflow. Standard deviation of the simulation normalised by the reference defined for the inflow data and standard deviation of the UAV by the mean over the data displayed. In contrast to Figure 6 only flights of one measurement day are used to reduce the influence of varying inflow speeds on the statistics.
Looking at the flow inclination\(^5\) in Figure 6, which is one of the important features in complex terrain siting [3], a strong upward inclined flow — with inclination angles up to 16° — following the terrain shape can be noticed for the simulation, which can also be seen in Figure 8, displaying the inclination angle as a contour plot extracted in a plane 100 m above ground. Close to the escarpment, at \(M_4\), the angle is up to 12° and in 100 m above ground around 10°. The lidar data do not capture the high flow angles, whereas the UAV data show good agreement above 100 m height and poor agreement closer to the surface. Further downstream at \(M_3\) the angle of the simulation reduces to a maximum of 8°. Lidar predicts angles around zero again and the UAV shows in general the same trends of the angle reduction as the simulation does. Approaching the met mast, the inclination reduces to almost zero at \(M_2\) as the wind profile recovers. The correlation between all data examined is satisfying at \(M_2\). Against the expectations, the inclination angles of UAV and lidar increase at \(M_1\) to about 5°. The met mast is located in a dip of terrain. Hence, small negative or zero inclination angles are expected, as seen in the simulation data. The differences might be caused by the temporal and spatial averaging process of the UAV which smears the strongly local topographic effect. Overall, reasonable agreement between all measurement data and the simulation where shown. Each approach captures the mean wind field at the test site properly and in accordance to the expectations from literature. Nonetheless, some shortcomings were seen. The UAV data showed differences in the standard deviations to the simulation. A future step is the study of different flight paths and averaging procedures. Considering flow angles, the lidar data differed from the rest of the data set. This point could not finally be clarified and is still under investigation. Maybe future measurements can help to overcome this issue. A possible source of error from the simulation side is the lack of a forest representation. A forest can mainly influence the flow field especially close to the ground. Nonetheless, the forest in the terrain can be considered as not too deep and the influence should therefore be small.

The results obtained from the above analysis shall be used for a recommendation for suitable position for a future wind turbine test site in the Stötten–area. This new test site is intended to cover disturbed flow conditions and shall contain two similar turbines, one closer to the escarpment and another one further downstream, as well as several met masts. Some of the key criteria for the evaluation are the power increase (Figure 8) or speed–up at the site, turbulent fluctuations and the flow inclination among other non–flow–physical facts like geological structure or bird protection. As seen in Figure 6 and 8 the massive speed–up lasts till 200 m downstream the escarpment, leading to higher potential power output about the factor two of a position in the valley upstream the escarpment. Further downstream the speed reduces, with regards to this aspect a position even 500 m downstream seems to be suitable. The same is true for the standard deviation which is nearly constant at top of the escarpment. Higher loads and power as well as similar fluctuations in comparison with a flat terrain situation can be expected until 500 m downstream of the escarpment. A locally more restricting picture is drawn by the inclination angles. Those keep above 10° until 100 m downstream the escarpment and are approaching zero in 100 m height above ground, approximately 200 m downstream the escarpment. This observation is supported by the wind speed profiles in Figure 6, displaying a strong deformation of the profile close to the ground for \(M_4\) and \(M_3\). Emerging from the results the position of the first turbine is suggested to be closer than 200 m to the escarpment and the other turbine should be placed further downstream. In this setup a doubling of possible power of the turbines is expected from the speed–up of about 25%, whereas the inclination will counteract this effect and reduce power. The full wind profile at the edge of the escarpment will lead to constantly high loads over one revolution and less fluctuations compared to a flat terrain situation. The turbine further downstream will experience less inclination angles and

\(^5\) Angle of the flow against the horizontal plane
Figure 8: Inclination angle (left) and relative power (right) in a plane in constant height above ground of 100 m. The black lines indicate height levels.

may have a higher power output depending on the wake situation. The wakes of both turbines are expected to be deflected as a result of the inclination angles, an effect comparable to yawed inflow which has been commonly studied e.g. by [33, 34, 47, 48].

6. Summary
The present article showed an extract of results from measurements and a simulation performed in the Southern German projects Lidar complex and KonTest [49]. A test site under featuring a steep escarpment was studied and described briefly before important aspects of UAV, lidar, met mast and simulation setup were highlighted. Different approaches were used to determine flow angles, mean wind speed and standard deviations, among others. As inflow conditions for the simulation a generic flow field based on the met mast data was created. This approach was validated by the fact that the wind profile recovers from the escarpment to the met mast. Therefore, the profile in the valley can be estimated as similar to the one at met mast. The lidar was used as wind profiler performing a modified VAD scan of the flow at different positions downstream the escarpment. The UAV collected data over several flights, covering the range of the lidar measurements. Comparing the measurements with each other and to the simulation’s shortcomings of the lidar predicting the inclination angle and the UAV determining turbulent fluctuations were seen. The latter aspect was considered to be based on the averaging procedure and the flight plan. Future investigations will be performed on these aspects. With regards to flow physics, a dominant speed-up and increase of inclination angles at the escarpment were seen as well as the reduction of the standard deviation. This effect remains visible far downstream the escarpment but starts to reduce in strength after about 200 m. In contrast to this, the inclination angle effect appears more locally and is nearly faded 200 m downstream the escarpment. As a last point, a recommendation for the position of a future wind turbine test site was made. A position of the first turbine closer than 200 m to the escarpment to cover inclination angles above 10° and a speed-up up to 25% was found to be preferable in case of neutral stratification. Future turbines at the new test site are expected to have constantly high loads over one revolution, increased mean loads and power compared to a flat terrain situation and a deflected wake. New numerical simulations will include a test turbine at the site to verify these statements [50].

Acknowledgements
The authors acknowledge the German Federal Ministry for Economic Affairs and Energy for funding this studies in the framework of the German joint research project Lidar complex and KonTest, the State Agency for Spatial Information & Rural Development Baden-Württemberg for providing terrain data and the High Perfomance Computing Center Stuttgart for the contribution of the computational resources. Moreover, thank you very much to all staff IAG, SWE and the University of Tübingen involved in the investigations.
