Weather Forecasts
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Genossenschaft METEOTEST
Fabrikstrasse 14, CH-3012 Bern
Tel. +41 (0)31 307 26 26
Fax +41 (0)31 307 26 10
office@meteotest.ch, www.meteotest.ch

Report on typical patterns in the temporal evolution of the vertical wind profile during Bora events (D-4.3)

Comparison of SODAR and LIDAR profiles (D-4.4)

Authors:
Saskia Bourgeois
René Cattin

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2. Comparison of SODAR and LIDAR profiles

2.1. Introduction

SODAR (SOund Detecting And Ranging) and LIDAR (LIght Detecting And Ranging) are two different remote sensing techniques capable to measure wind speed and wind direction up to 200 m above ground. While the SODAR technique is based on acoustic impulses the LIDAR technique is based on optic impulses. Both instruments have in common that the impulses are sent to the atmosphere. From the Doppler shift of the reflected signal wind speed and wind direction can be calculated for various heights. Both instruments have been developed for the wind industry for measuring vertical wind profile at great heights.

SODAR instruments are on the market for more than twenty years and have been used for many wind site assessments. A number of models from different manufacturers are currently on the market. SODAR measurements are generally well accepted in the wind industry. Studies have shown that with SODAR relative wind speed profiles can be measured very accurately while the absolute values of the measured wind speed often show a bias compared to cup anemometer measurements[1]. Therefore only normalised values of SODAR measurements, or SODAR data scaled to cup anemometer data are used for wind studies.

LIDAR instruments have been introduced in the wind industry within the last four years. Up to now only few studies exist proving the potential of LIDAR for wind measurements. However, all these studies showed promising results. Compared to the SODAR technology not only relative values but also absolute values from LIDAR measurements are very accurate[2].

2.2. Measurements

During the SEEWIND project concurrent SODAR and LIDAR measurements were carried out at two sites, Maligrad (Bosnia and Herzegovina) and Rudine (Croatia). For documentations and results of the individual measurement campaigns, see deliverables D-4.1 and D-4.2.

One goal of the concurrent measurement campaigns was to compare the data sets of both instruments. All relevant components were analysed, i.e. wind speed, wind direction and turbulence intensity. The second goal was to test the suitability of SODAR and LIDAR instruments in complex terrain and under harsh climatic conditions (see also deliverable D-4.5).

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1 Warmbier et al, 2006, Verification of wind energy related measurements with a SODAR system, Windpower 2006.

2 Albers et al. 2008. Comparison of LIDARs, German test station for remote wind sensing devices. DEWEK 2008.

2.3. Results

Comparisons of SODAR and LIDAR data were elaborated for both measurement campaigns. The findings were presented at three conferences and are summarized in the following three papers:

1. S. Bourgeois, R. Cattin, I. Locker, H. Winkelmeier; EWEC2008. Analysis of the vertical wind profile at a Bura-dominated site in Bosnia based on SODAR and ZephIR LIDAR measurements.

2. S. Bourgeois, R. Cattin, H. Winkelmeier, I. Locker; DEWEK2008. CFD modeling of the vertical wind profile and the turbulence structure above complex terrain and validation with SODAR and LIDAR measurements.

3. S. Bourgeois, R. Cattin, H. Winkelmeier, I. Locker; EWEC2009. CFD modeling of the vertical wind profile and the turbulence structure above complex terrain and validation with SODAR and LIDAR measurements.

The following section contains the extended abstracts of the above mentioned studies.

ANALYSIS OF THE VERTICAL WIND PROFILE AT A BURA-DOMINATED SITE IN BOSNIA BASED ON SODAR AND ZEPHIR LIDAR MEASUREMENTS

Saskia Bourgeois[1], René Cattin[1], Ian Locker[2], Hans Winkelmeier[3]

(1) bourgeois@meteotest.ch, Meteotest, Fabrikstrasse 14, 3012 Bern, Switzerland, Tel. +41 31 307 26 26
(2) The Natural Power Consultants Ltd., Malvern Technology Centre E708, St Andrews Road, Malvern, WR14, U.K.
(3) Verein Energiewerkstatt, Heiligenstatt 24, 5211 Friedburg, Austria

ABSTRACT

Knowledge of the shape of the vertical wind profile is an important issue particularly for site assessments and energy yield calculations. Strong efforts in the remote sensing technology yielded to state of the art wind measuring instruments like SODARs (SOund Detecting And Ranging) and LIDARs (LIght Detecting And Ranging).

This study presents a wind measurement campaign carried out in Bosnia near Mostar where the terrain was medium complex and the winds were known to be some times very strong and turbulent. A special attention was given to the so called Bora wind, a gusty wind from the north north-east. One goal of the study was to examine the performance of an Aerovironment SODAR and a ZephIR LIDAR under these harsh meteorological conditions in complex terrain. A 30 m mast provided cup anemometer data.

Both, the SODAR and the LIDAR showed a very good performance with high data availability up to 100 m above ground. Measured wind speeds and wind directions agreed well with the 30 m mast data. While the deployment and the data processing of the SODAR was more demanding the LIDAR proved to be more user friendly.

The vertical wind profiles showed almost no increase with height for both prevailing wind directions and the turbulence intensity was only slightly higher during Bora wind events.

1. INTRODUCTION

The main objective of the project SEEWIND (South East Europe Wind Energy Exploitation) - embedded in the 6th framework program of the European Commission - is to gain experience in wind measurement, site development and operation of large scale wind turbines at sites in complex terrain and especially under the specific geographic and climatic conditions in the West Balkan area with the aim of increasing efficiency and reliability of wind turbine technology. The SEEWIND project started in May 2007 and has a duration of 36 months. It is coordinated by Verein Energiewerkstatt from Austria, the project partners are Meteotest (CH), DEWI and DEWI-OCC (D), Vjetroenergetika (BO), Adria Wind Power (HR), Univerzitet 'Dzemal Bijedic' u Mostar and the Federal Meteorological Institute of Bosnia and Herzegovina (BO).
Knowledge on the shape and the behaviour of the vertical wind profile is crucial for energy yield assessments in such terrain, e.g. for the verification of model simulations. Remote sensing techniques such as SODAR and LIDAR play an important role in this process. Thus, the work package "Vertical wind profile in complex terrain" of the SEEWIND project is dedicated specifically to the evaluation of this question. Within this work package, detailed analysis not only of the average vertical wind profiles but also of the temporal evolution of the vertical wind profile during Bura events were carried out.
A three-month measurement campaign with an Aerovironment 4000mini SODAR was performed at the Podvelez Plateau near the city of Mostar, Bosnia starting in fall 2007. The wind flow at the Podvelez plateau is mainly caused by the Adriatic wind system called "Bora" which is generated by different levels in temperature and air pressure between the Adriatic Sea and mainland of the South-East Balkan area. Additionally, the East-West course of the Neretva valley leads to a strong canalization effect.

In parallel to the SODAR measurement, a three-week measurement campaign with the ZephIR LIDAR system was carried out at the same location. The goal of the measurement campaign was to enhance the knowledge concerning the suitability of LIDAR for wind energy assessments in such complex environment.

2. SITE DESCRIPTION

The measurement site called Maligrad (Figure 1) is located on the high plateau Podvelez approximately 5 km east of the city of Mostar in Bosnia-Herzegovina. The instruments were installed at a height of 730 m asl. To the east there are two other hills reaching up to 880 m asl and 1'060 m asl, respectively. A mountain chain Velez (1'800 m asl) overshadows the site Maligrad further east. To the north north-west, west and south-west, the terrain lowers down to around 50 m asl in Mostar.
The prevailing wind directions are north north-east (Bora) and south. Wind speeds are very variable and can easily reach 20 m/s at 30 m height. Figure 2 shows the wind rose at Maligrad at 30 m as measured at the mast.

Figure 1: The measurement site Maligrad with the SODAR (left) and the ZephIR LIDAR (right).

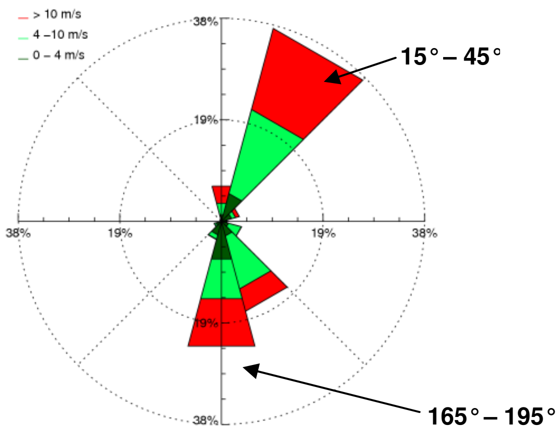

Figure 2: Wind rose measured at the met mast at 30 m with the two prevailing wind directions sectors 15°-45° and 165°-195°.

3. MEASUREMENT CONFIGURATION

The analyzed period for this study started 22 November 2007 and ended 9 December 2007. In table 1 the measurement configuration and measurement periods of the 30 m mast, the SODAR and the LIDAR are shown.

Table 1: Measurement configuration.

	measurement height of wind speed	measurement height of wind direction	measurement period
30 m mast, cup anemometers: Thies Classic (uncalibrated)	12 m; 30 m	30 m	May 2005 – in course
SODAR (Aerovironment 4000 miniSODAR, ASC)	30 m to 150 m with 10 m resolution	30 m to 150 m with 10 m resolution	30 Oct '07 – 4 Feb '08
LIDAR (ZephIR, Natural Power)	30 m; 60 m; 80 m; 100 m; 150 m	30 m; 60 m; 80 m; 100 m; 150 m	21 Nov '07 – 10 Dec '07

4. RESULTS

4.1. Comparison of the data availability

While for the SODAR data some obvious outliers were filtered out, all measured data from the LIDAR have been used in this study. The LIDAR data are available only for five levels. At 100 m above ground the data availability is still 85% (Figure 3, left). The SODAR data are available at a vertical resolution of 10 m, however the data availability decreases rapidly with height. At 100 m above ground the data availability is reduced to 54% (Figure 3, right).

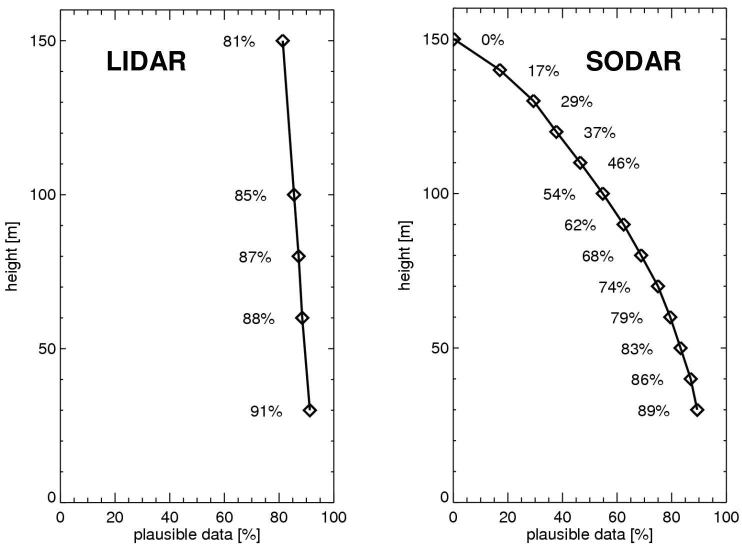

Figure 3: Data availability as a function of the height for the LIDAR (left) and the SODAR (right).

4.2. Comparison of the measured wind speed

A comparison of the measured wind speeds at 30 m is shown in Figure 4 with scatterplots and the evaluated regression and correlation coefficients. The data is displayed for the two prevailing wind direction sectors. Plausible LIDAR data are available for wind speeds well above 20 m/s and show a good correlation to the cup anemometer data (Figure 4, top). The quality of the SODAR data decreases rapidly for wind speeds > 15 m/s and the correlation with the cup anemometer data shows pronounced differences depending on the considered wind sector (Figure 5, bottom).

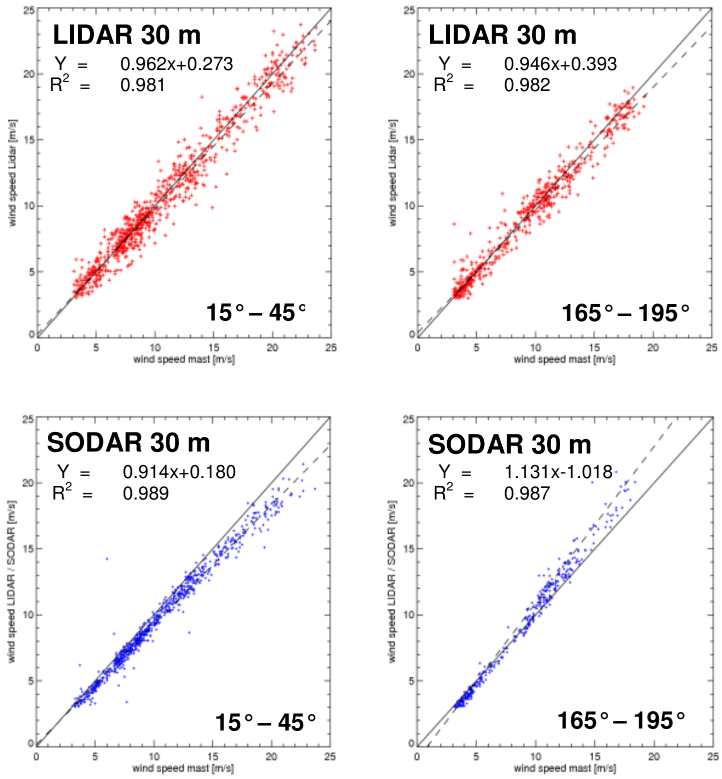

Figure 4: Scatterplot of the 30 m wind speed (10-min averages): cup anemometer – LIDAR (top) and cup anemometer – SODAR (bottom), for the wind sectors 15-45° (left) and 165-195° (right).

4.3. Comparison of the measured wind direction

Figure 5 shows the time series of the measured wind directions for the height of 30 m for the SODAR (green), the mast (red) and the LIDAR (blue).

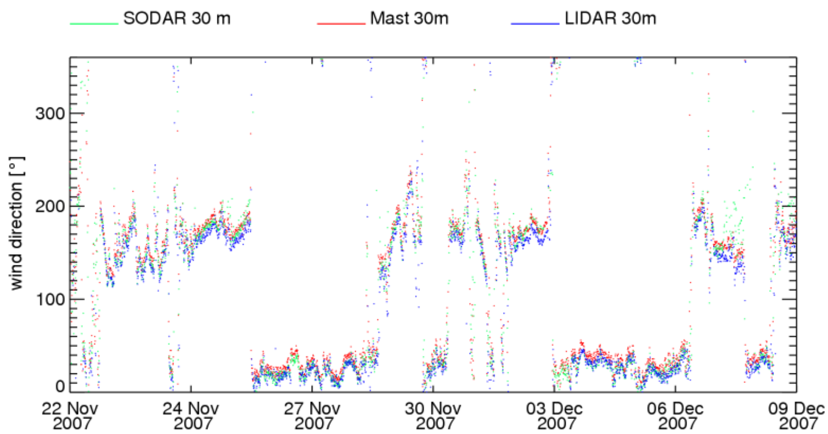

Figure 5: Time series of the 10-min averaged wind direction data for SODAR (green), LIDAR (blue) and mast (red) at 30 m .

4.4. Comparison of the turbulence intensity

As shown in figure 6 the calculated turbulence intensity of cup, LIDAR and SODAR in the sector 15°- 45° agree very well (figure 6, top). For the sector 165°-195° (figure 6, bottom) a shift can be seen between the cup anemometer data and the LIDAR data. Also in this sector the turbulence intensity from the SODAR data shows strong discrepancies to LIDAR and cup anemometer data.

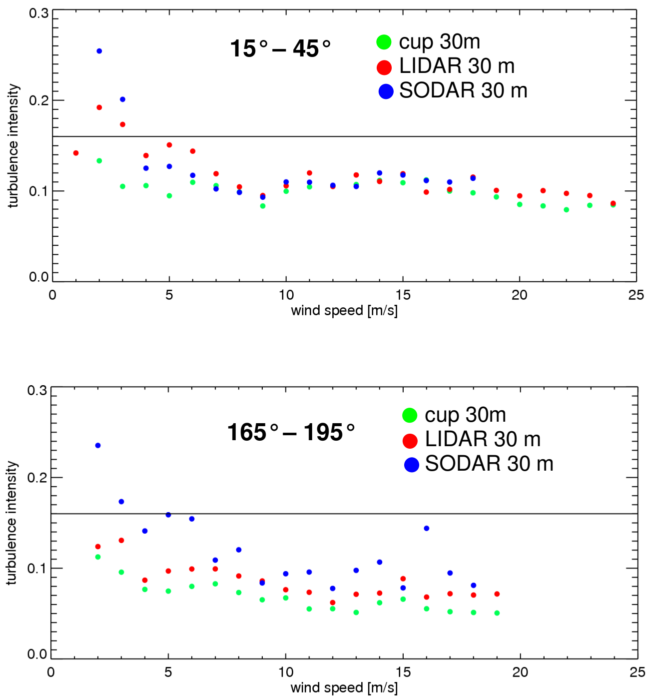

Figure 6: Turbulence intensity of cup anemometer data (green), LIDAR data (red) and SODAR data (blue) at the height of 30 m for the sector 15°- 45° (top) and 165°-195°(bottom).

4.5. Vertical profiles of the wind speed

Figure 7 shows the vertical wind profile for the two prevailing wind direction sectors. In general the increase with height is very small and the vertical wind profiles of LIDAR and SODAR agree very well in the sector 15°- 45° (figure 7, left). However, in the south sector 165° - 195° (figure 7, right) the SODAR data shows a stronger increase with height than the LIDAR data.

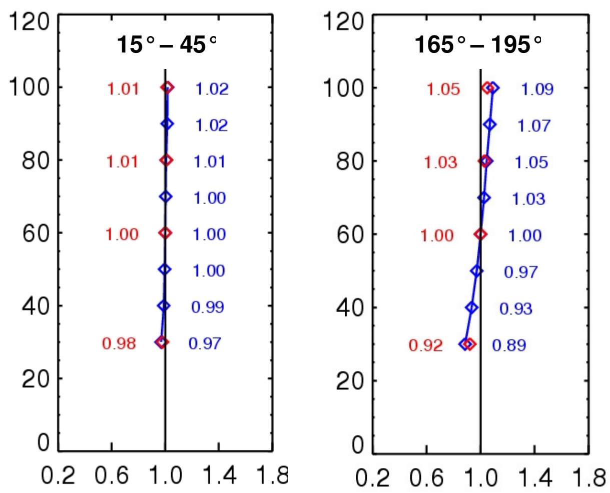

Figure 7: Vertical wind profiles normalized to 60 m of the LIDAR data (red) and the SODAR data (blue) for the prevailing wind direction sectors 15°-45° (left) and 165°-195° (right).

5. SUMMARY AND CONCLUSIONS

Comparison SODAR - LIDAR:

- The LIDAR and the SODAR system showed both a very good performance under the extreme climatic conditions at Maligrad with cold temperatures, heavy rain fall, snow fall and turbulent winds often exceeding 20 m/s.
- The LIDAR has a remarkably higher data availability compared to the SODAR.
- The quality of SODAR data decreases rapidly at wind speeds >15 m/s and for higher levels.
- The transport and installation of the LIDAR is more user friendly compared to the SODAR.
- GSM data transfer of the LIDAR was slow and unstable.

Wind regime at the study site:

- The increase of wind speed with height is very small.
- Turbulence intensities are higher for the sector 15°- 45° (Bora wind) than for the sector 165°-195°. However, the turbulence intensities for both prevailing wind directions are still below class A and B of the IEC.

ACKNOWLEDGEMENTS

The measurement campaign at Maligrad was financed by the 6th framework program of the European Commission (TREN/07/FP6EN/S07.70669/038489) and the local project developer Vjetroenergetika BH. The authors wish to thank Nikola Maric for his excellent technical support at the measurement site.

CFD MODELING OF THE VERTICAL WIND PROFILE AND THE TURBULENCE STRUCTURE ABOVE COMPLEX TERRAIN AND VALIDATION WITH SODAR AND LIDAR MEASUREMENTS

Saskia Bourgeois[1], René Cattin[1], Hans Winkelmeier[2], Ian Locker[3]
[1]Meteotest, Bern, Switzerland, +41 31 307 2626, saskia.bourgeois@meteotest.ch
[2]Verein Energiewerkstatt, Friedburg, Austria, [3]The Natural Power Consultants, Malvern, Worcs, UK

Summary

Vertical profiles of wind speed and turbulence intensity were modeled with the CFD model WindSim for a site in medium complex terrain in Croatia. The results were validated against SODAR and LIDAR measurements. A 50 m mast provided cup anemometer data.
The wind measurement campaign was carried out in Rudine/Croatia about 35 km north of Dubrovnik near the Adriatic coast. At this site the winds are known to be sometimes very strong. In particular the so called Bora, a gusty wind from north to north-east. One goal of the campaign was to examine the performance of SODAR and LIDAR instruments under harsh meteorological conditions. Both, SODAR and LIDAR showed very good performance with high data availability up to 100 m. Vertical profiles of wind speed showed only small increase with height for the prevailing wind directions north north-east and south south-east. Turbulence intensities calculated from SODAR and LIDAR measurements showed different values as a result of different sampling rates. However both data sets revealed almost constant turbulence intensities between 30 m and 100 m above ground. Turbulence intensities remained below class A of the IEC 61400.
For comparison the vertical profiles of WindSim, SODAR and LIDAR measurements were normalised to 50 m for all twelve 30° wind direction sectors. The normalised vertical wind speed profiles of SODAR, LIDAR and WindSim showed good agreement especially for the prevailing wind directions. Turbulence intensities calculated by WindSim show a weak decrease with height in contrary to the almost constant vertical turbulence intensity profiles of the SODAR and LIDAR measurements.

1. Introduction

The South East Europe Wind Energy Exploitation (SEEWIND) project [1], embedded in the 6th framework program of the European Commission, aims to gain experience in wind measurements, site development and operation of wind turbines in complex terrain. In order to get information about the vertical wind profile at two Bora-dominated sites in Bosnia and Croatia, SODAR and LIDAR measurements were carried out. Bora is a strong katabatic wind from north to north-east. Knowledge of the vertical wind profile and the turbulence intensities on Bora dominated sites will provide important information on the impact on a wind turbine operating under such conditions.
This study investigates vertical wind speed profiles and turbulence intensities at Rudine, a Bora dominated site in Croatia and evaluates the performance of the CFD modeling software WindSim [2] regarding the vertical profiles of wind speed and turbulence intensities.

2. Site Description and Instrumentation

The measurement site Rudine is located on a high plateau on the mainland of Croatia, about 35 km north-west of Dubrovnik, approximately 380 m above sea level (Fig. 1). The region is dominated by Karst and only low vegetation and the terrain can be described as medium complex.
A mast provided wind speed and wind direction data at 50 m height. Mast data were cleaned and corrected for long term conditions by the SEEWIND partner DEWI [3]. Fig. 2 shows the wind rose at Rudine at 50 m height from the mast measurement. The prevailing wind directions are north north-east and south south-east.
The installed SODAR was of type Aerovironment miniSODAR 4000F and the measurement heights ranged from 30 m to 150 m with 10 m intervals. The measuring rate was approximately 0.33 Hz and the averaging interval 10 minutes. The LIDAR was of type ZephIR [4] and the five measurement levels were set to 30, 50, 80, 100 and 150 m. The measuring rate was approximately 0.05 Hz and the averaging interval 10 minutes.
SODAR and LIDAR were installed within a distance of 10 m. The mast was located approximately 35 m away from SODAR and LIDAR to the south-east (Fig. 3). SODAR and LIDAR data were available only for a limited time period, this is 12 February to 5 May 2008 for the SODAR and 9 April to 5 May 2008 for the LIDAR. Only the period when both instruments were in use are considered for this data evaluation.

3. CFD Model WindSim

WindSim is a CFD-package for micrositing based on the more general CFD solver Phoenics. The CFD simulations are based on the integration of Reynolds Averaged Navier-Stokes (RANS) equations over a portion of the lower atmosphere. The RANS equations are discretised on a computational grid and integrated with a finite-volume procedure. Turbulence is calculated using the standard k-epsilon turbulence model which allows closing the set of equations. WindSim is able to assess wind resources with a high degree of accuracy. Even terrain with fairly complex features can be processed with WindSim. Three primary inputs are necessary to run WindSim, first a digital elevation model, second a roughness map and third a climatology. All these data sets were compiled and provided by the SEEWIND partner DEWI. WindSim offers the possibility to extract vertical profiles of various parameters, like for example wind speed and turbulence intensity, and that for each modeled height and sector. The values of the vertical WindSim profiles are only relative values which have to be scaled with a climatology. Tab. 1 lists the dimensions and grid sizes of the WindSim model calculations for the base and the nested model.

Tab. 1: Dimensions and grid sizes of WindSim.

Model	Base model	Nested model
Extension	14 x 11 km	6 x 3.5 km
Horizontal grid size	100 m	18.7(center) - 86.6 m 19.5(center) - 86.5 m
First 7 vertical levels above ground	12.8, 42.7, 80.9, 127.5, 182.5, 245.8, 317.6 m	5.5, 12.2, 34.0, 54.0, 77.0,103.3, 133.3 m

4. Methods

4.1 Vertical Wind Speed Profiles

Vertical wind speed profiles of SODAR and LIDAR measurements are only analysed qualitatively in this study, which means that only normalised data sets are compared. Wind speed profiles from both instruments are analysed for twelve 30° wind direction sectors. Furthermore the normalised vertical wind speed profiles of the WindSim model output are validated using LIDAR measurements.

4.2 Vertical Turbulence Intensity Profiles

Turbulence intensities (TI) from SODAR and LIDAR measurements are evaluated by calculating the ratio of the standard deviation wind speed ($sigma_U$) to the mean wind speed (U) according to the following formula: TI = $sigma_U/U$. Only wind speeds above 4 m/s are considered. As a consequence of the different sampling rate of SODAR and LIDAR standard deviations cannot be compared quantitatively. Finally vertical profiles of the turbulence intensities calculated by WindSim are verified using LIDAR measurements.

5. Results

5.1 Vertical Wind Speed Profiles

Comparison of SODAR and LIDAR Measurements

Fig. 4 and Fig. 5 show the vertical profiles of the wind speed from SODAR and LIDAR measurements for the main wind directions north north-east and south south-east and for different wind speed classes. The data sets are normalised to 50 m height. The increase of the mean wind speed from 50 to 100 m is in general small for the main wind directions, 6% and 5% considering the SODAR and 4% considering the LIDAR data. The profile shape is independent to the wind speed. The outlier in the SODAR profile at 40 m height is probably a result of an echo during data collection.

Comparison of LIDAR Measurements with WindSim

The levels of the WindSim model output do not agree with the measurement levels of the LIDAR. For comparison reason the wind speed data of the WindSim output level from 54 m was reduced linearly to 50 m and the model output data are normalised to this interpolated value. In Fig. 6 the vertical wind profiles normalised to 50 m from LIDAR measurements and WindSim model are compared for the two main wind directions. WindSim produces an increase from 50 to 103.3 m of 10% and 7% respectively; this means a slightly larger increase than seen in the measurements.

5.2 Vertical Turbulence Intensity Profiles

Comparison of Turbulence Intensities from SODAR and LIDAR

Fig. 7 and Fig. 8 show the calculated turbulence intensities from SODAR and LIDAR measurements up to 100 m height for the main wind direction sectors. Both data sets show an almost constant turbulence with height with a higher intensity of turbulence for the sector north north-east. The constant bias between SODAR and LIDAR data can be explained by different data sampling rate (see section 2).

Comparison of LIDAR and WindSim Turbulence Intensities

Fig. 9 shows the turbulence intensities from LIDAR measurements and WindSim calculations for 30° wind direction sectors. LIDAR turbulence intensities are calculated only for wind speeds above 4 m/s. No turbulence was calculated for sectors/levels with less than ten valid 10 minute averages. General patterns of the WindSim turbulence intensities agree well with the LIDAR measurements. In the WindSim output the decrease of the turbulence intensity is more pronounced than in the LIDAR measurements. The agreement of the values for the main wind directions is a coincidence.

6. Conclusions

- Only small increase of wind speed with height at Rudine.
- Constant turbulence intensity up to 100 m height at Rudine.
- Good agreement of SODAR, LIDAR and WindSim vertical wind speed profiles.
- Determination of turbulence intensity difficult due to different sampling rate. More investigations on calculation of turbulence intensities are needed.

References

[1] SEEWIND, http://www.seewind.org/ (18.9.2008)
[2] WindSim, http://www.windsim.com/ (18.9.2008).
[3] DEWI, GmbH, Deutsches Windenergie-Institut
[4] LIDAR ZephIR, http://www.naturalpower.com/zephir-laser-anemometer (18.9.2008)

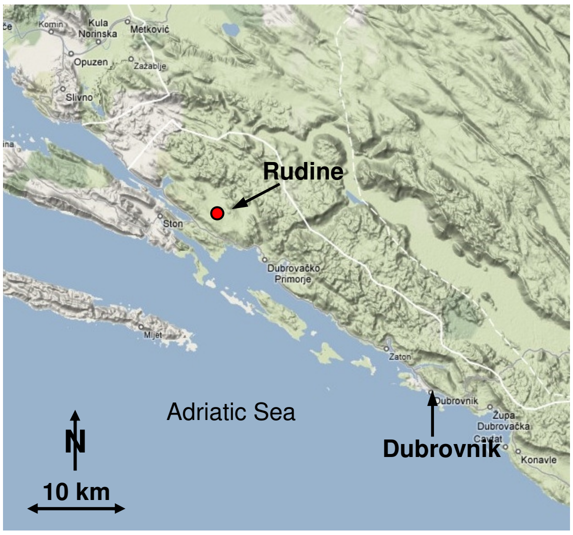

Fig. 1: Map of south Croatia with the wind measurement site Rudine.

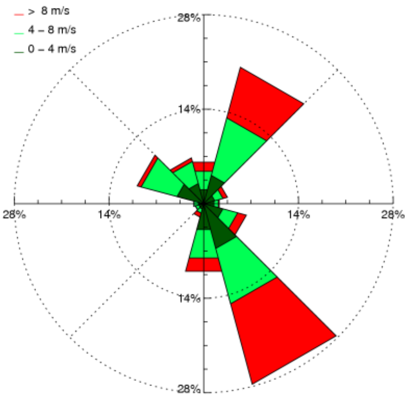

Fig. 2: Wind rose at Rudine at 50 m height.

Fig. 3: Picture of SODAR (left), 50 m mast and LIDAR (right) at Rudine facing south-east.

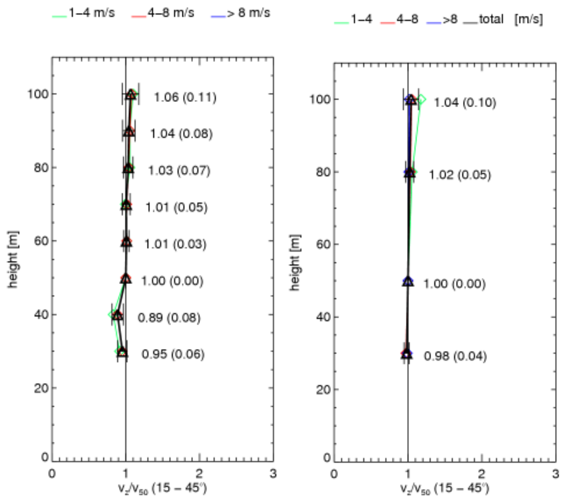

Fig. 4: Vertical wind speed profiles from SODAR (left) and LIDAR (right) normalised to 50 m for the wind direction north north-east, in brackets the standard deviations.

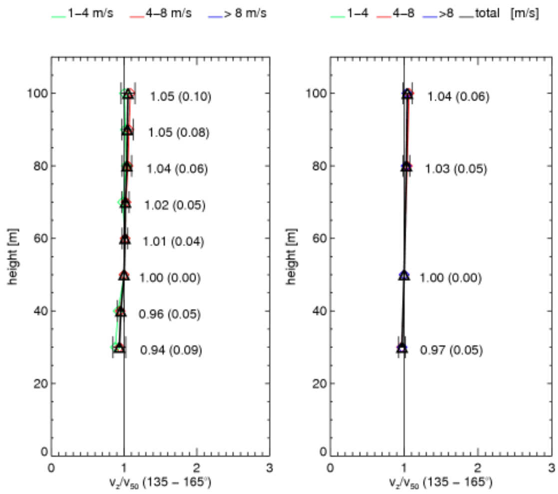

Fig. 5: Vertical wind speed profiles from SODAR (left) and LIDAR (right) normalised to 50 m for the wind direction south south-east, in brackets the standard deviations.

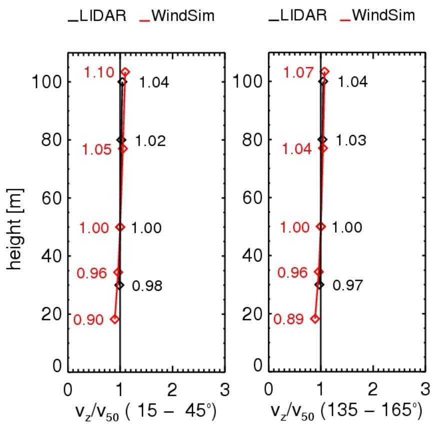

Fig. 6: Comparison of vertical wind speed profiles from WindSim and LIDAR data normalised to 50 m for the wind directions north-north-east (left) and south south-east (right).

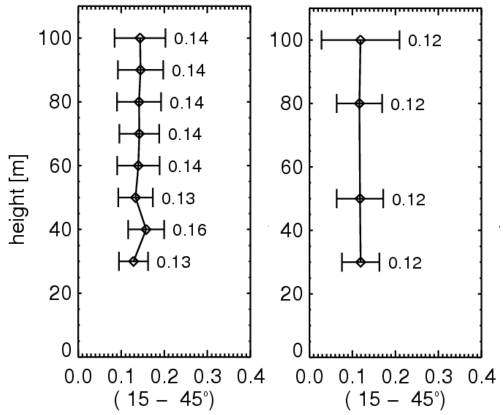

Fig. 7: Comparison of vertical turbulence intensity profiles from SODAR (left) and LIDAR (right) data for the wind direction north north-east. The bars indicate the standard deviation.

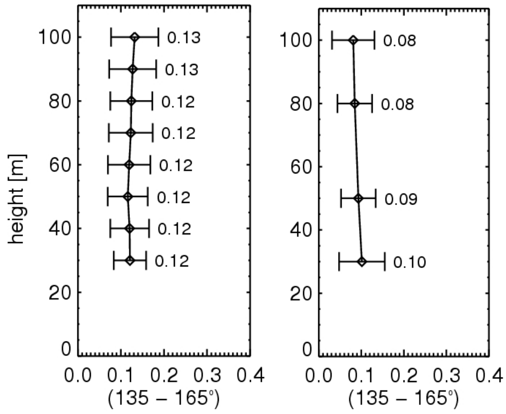

Fig. 8: Comparison of vertical turbulence intensity profiles for SODAR (left) and LIDAR (right) data for the wind direction south south-east. The bars indicate the standard deviation.

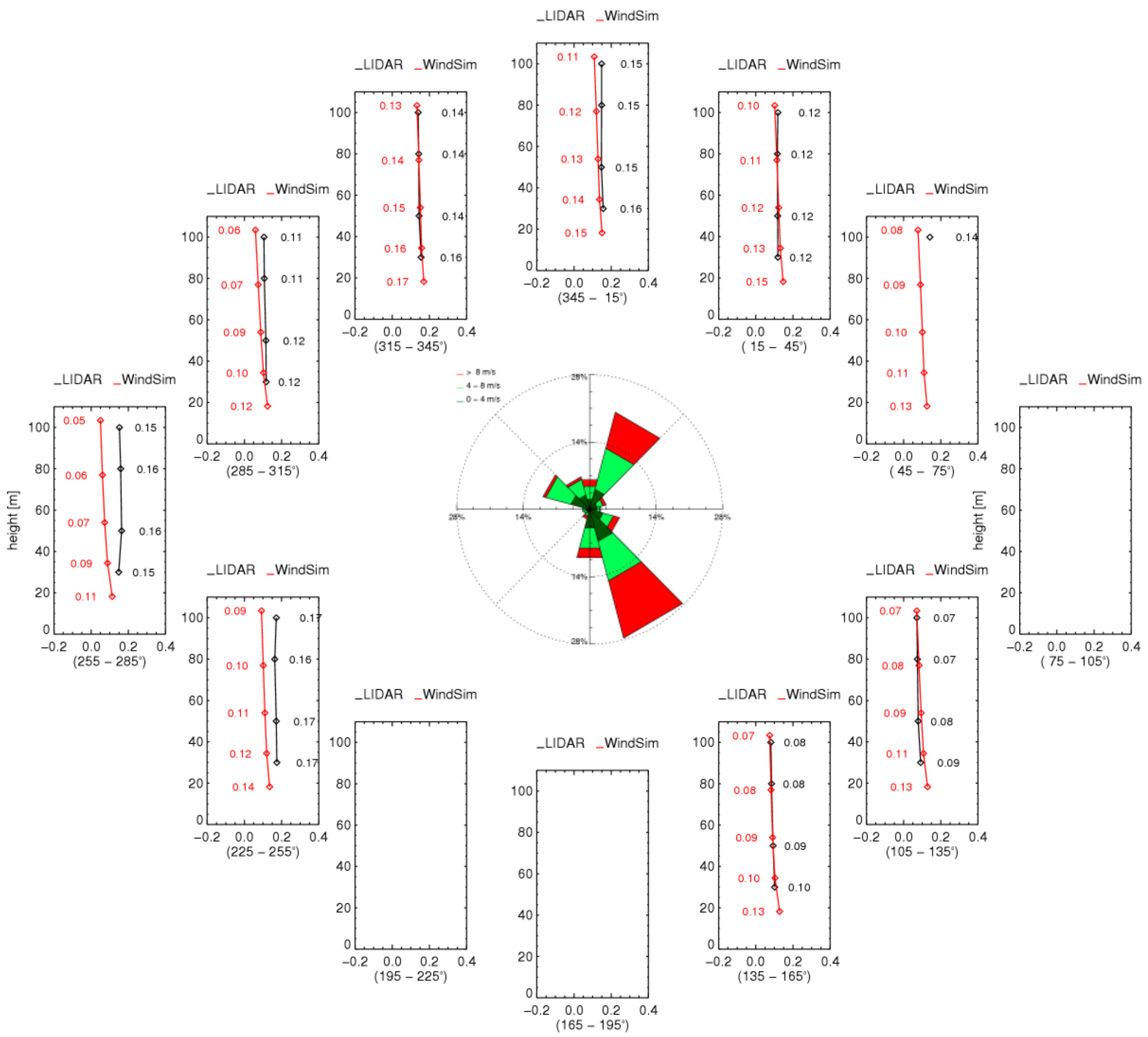

Fig. 9: Vertical profiles of turbulence intensities for 30° wind direction sectors from LIDAR measurements (black) and WindSim calculations (red) at Rudine. In the center the wind rose at 50 m from the mast measurement is displayed. Turbulence intensities are calculated only for wind speeds above 4 m/s. No turbulence was calculated for sectors/levels with less than ten valid 10 minute averages for the LIDAR measurements.

CFD MODELING OF THE VERTICAL WIND PROFILE AND THE TURBULENCE STRUCTURE ABOVE COMPLEX TERRAIN AND VALIDATION WITH SODAR AND LIDAR MEASUREMENTS

Saskia Bourgeois[1], René Cattin[1], Hans Winkelmeier[2], Ian Locker[3]

(1) saskia.bourgeois@meteotest.ch, Meteotest, Fabrikstrasse 14, 3012 Bern, Switzerland, Tel. +41 31 307 26 26
(2) Verein Energiewerkstatt, Heiligenstatt 24, 5211 Friedburg, Austria
(3) The Natural Power Consultants Ltd., Malvern Technology Centre E708, St Andrews Road, Malvern, WR14, U.K.

ABSTRACT

Vertical profiles of wind speed and turbulence intensity were modeled with the CFD model WindSim for two sites in medium complex terrain in Maligrad/Bosnia and Rudine/Croatia. The results were validated against SODAR and ZephIR-LIDAR measurements. At both sites met masts (30 m at Maligrad and 50 m at Rudine) provided anemometer data. Both measurement campaigns were carried out at sites where the winds are known to be sometimes very strong and turbulent, in particular the so called Bora, a gusty wind from north to north-east.

One goal of the campaigns was to examine the performance of SODAR and LIDAR instruments under harsh meteorological conditions. SODAR and LIDAR showed very good performance with high data availability up to 100 m.

For comparison the vertical profiles of WindSim, SODAR and ZephIR-LIDAR were normalised to 30 m/50 m for twelve 30° wind direction sectors. The normalised vertical wind speed profiles of SODAR, LIDAR and WindSim showed good agreement especially for the prevailing wind directions. Vertical profiles of wind speed showed only small increase with height for the prevailing wind directions north north-east and south south-east.

Turbulence intensities calculated from SODAR and LIDAR measurements showed different values as a result of different sampling rates. Furthermore, turbulence intensities calculated by WindSim showed a weak decrease with height in contrary to the almost constant vertical turbulence intensity profiles of the SODAR and LIDAR measurements between 30 m and 100 m. Turbulence intensities remained below class A of the IEC 61400.

1. INTRODUCTION

The South East Europe Wind Energy Exploitation (SEEWIND) project [1], embedded in the 6th framework program of the European Commission, aims to gain experience in wind measurements, site development and operation of wind turbines in complex terrain. In order to get information about the vertical wind profile at two Bora-dominated sites in Bosnia and Croatia, SODAR and LIDAR measurements were carried out. Bora is a strong katabatic wind from north to north-east. Knowledge of the vertical wind profile and the turbulence intensities on Bora dominated sites will provide important information on the impact on a wind turbine operating under such conditions.

This study investigates vertical wind speed profiles and turbulence intensities at Maligrad (Bosnia) and Rudine (Croatia), two Bora dominated site in the West Balkan area and evaluates the performance of the CFD modeling software WindSim [2] regarding the vertical profiles of wind speed and turbulence intensities.

2. SITE DESCRIPTION

2.1 Maligrad/Bosnia

The first measurement site, Maligrad in Bosnia (Figure 1 and Figure 2), was located on the high plateau Podvelez approximately 5 km east of the city of Mostar in Bosnia. The instruments were installed at a height of 730 m asl. To the east there are two other hills reaching up to 880 m asl and 1’060 m asl, respectively. A mountain chain Velez (1’800 m asl) overshadows the site Maligrad further east. To the north north-west, west and south-west, the terrain lowers down to around 50 m asl in Mostar. The prevailing wind direction at Maligrad is north north-east (Bora). Wind speeds are very variable and can easily reach 20 m/s at 30 m height. Figure 3 shows the wind rose and the wind speed distribution including the approximated Weibull distribution at 30 m height for Maligrad.

2.2 Rudine/Croatia

The second measurement site, Rudine in Croatia (Figure 2), was located on a high plateau on the mainland of Croatia, about 35 km north-west of Dubrovnik, approximately 380 m above sea level. The region is dominated by Karst and only low vegetation and the terrain can be described as medium complex. The prevailing wind directions at Rudine are north north-east (Bora) and south south-east (Jugo). Wind speeds are also very variable. Wind speeds above 20 m/s at 50 m height have been observed occasionally. Figure 4 shows the wind rose and the wind speed distribution including the approximated Weibull distribution at 50 m height for Rudine.

Figure 1: The measurement site Maligrad with the SODAR (left) and the ZephIR-LIDAR (right).

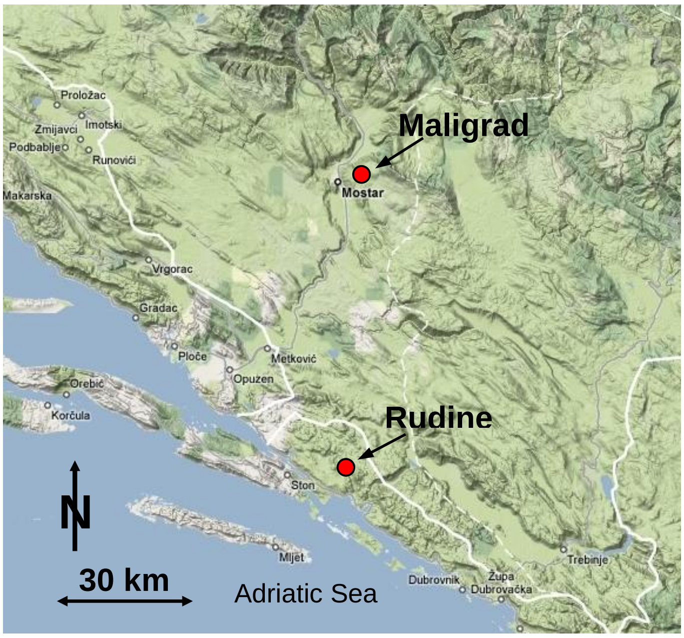

Figure 2: The measurement sites Maligrad in Bosnia and Rudine in Croatia.

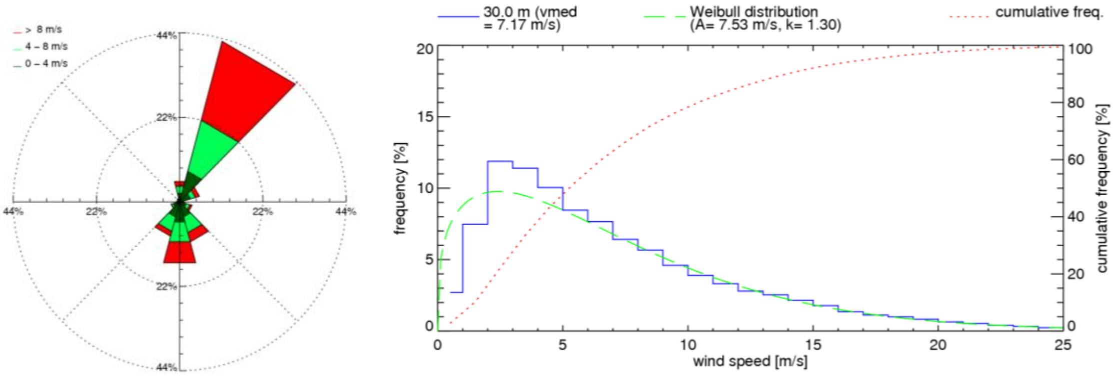

Figure 3: Wind rose and wind speed frequency distribution including approximated Weibull distribution at 30 m height (mast measurement) for Maligrad.

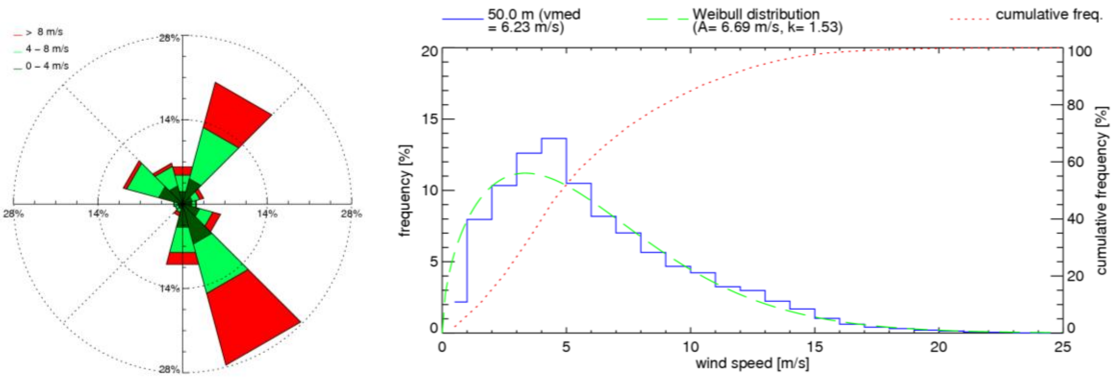

Figure 4: Wind rose and wind speed frequency distribution including approximated Weibull distribution at 50 m height (mast measurement) for Rudine.

3. INSTRUMENTATION AND DATA BASE

Wind speed and wind direction data were provided by a 30 mast at Maligrad and a 50 m mast at Rudine. Mast data were cleaned and corrected for long term conditions by the SEEWIND partner DEWI [3]. The installed SODAR was of type Aerovironment miniSODAR 4000F and the measurement heights ranged from 30 m to 150 m with 10 m intervals. The measuring rate was approximately 0.33 Hz and the averaging interval 10 minutes. The LIDAR was of type ZephIR [4]. The measuring rate was approximately 0.05 Hz and the averaging interval 10 minutes. The instruments' configurations and the measurement periods of masts, SODAR and ZephIR-LIDAR are summarized in Table 1 and 2.

Table 1: Instruments' configuration and measurement period at Maligrad.

	measurement heights of wind speed	measurement heights of wind direction	measurement periods
30 m mast, cup anemometers	12 m; 30 m	30 m	2006 – 2008
SODAR (Aerovironment 4000F miniSODAR, ASC)	30 m to 150 m with 10 m resolution	30 m to 150 m with 10 m resolution	30 Oct '07 – 4 Feb '08
LIDAR (ZephIR, Natural Power)	30 m; 60 m; 80 m; 100 m; 150 m	30 m; 60 m; 80 m; 100 m; 150 m	21 Nov '07 – 10 Dec '07

Table 2: Instruments' configuration and measurement period at Rudine.

	measurement heights of wind speed	measurement heights of wind direction	measurement periods
50 m mast, cup anemometers	30 m; 50 m	30 m	2007 – 2009
SODAR (Aerovironment 4000F miniSODAR, ASC)	30 m to 150 m with 10 m resolution	30 m to 150 m with 10 m resolution	12 Feb '08 – 5 May '08
LIDAR (ZephIR, Natural Power)	30 m; 50 m; 80 m; 100 m; 150 m	30 m; 50 m; 80 m; 100 m; 150 m	9 Apr '08 – 5 May '08

4. CFD MODEL WINDSIM

WindSim [2] is a CFD-package for micrositing based on the CFD solver Phoenics. The CFD simulations are based on the integration of Reynolds Averaged Navier-Stokes (RANS) equations over a portion of the lower atmosphere. The RANS equations are discretised on a computational grid and integrated with a finite-volume procedure. Turbulence is calculated using the standard k-epsilon turbulence model which allows closing the set of equations. WindSim is able to assess wind resources with a high degree of accuracy. Even terrain with fairly complex features can be processed with WindSim. Three primary inputs are necessary to run WindSim, first a digital elevation model, second a roughness map and third a wind climatology. All these data sets were compiled and provided by the SEEWIND partner DEWI [3] for Maligrad and Rudine.
WindSim offers the possibility to extract vertical profiles of various parameters for each modeled height and sector, for example for wind speed and turbulence intensity. The values of the vertical WindSim profiles are only relative values which have to be scaled with a climatology.

5. METHODS

5.1 Vertical Wind Speed Profiles Vertical wind speed profiles of SODAR and LIDAR measurements are only analysed qualitatively in this study, which means that only normalised data sets are compared. Wind speed profiles from both instruments are analysed for twelve 30° wind direction sectors. Furthermore normalised vertical wind speed profiles of the WindSim model output are validated using LIDAR measurements.

5.2 Vertical Turbulence Intensity Profiles

Turbulence intensities (TI) from SODAR and LIDAR measurements are evaluated by calculating the ratio of the standard deviation wind speed ($sigma_U$) to the mean wind speed (U) according to the following formula: $TI = sigma_U/U$. Only wind speeds above 4 m/s are considered. As a consequence of the different sampling rate of SODAR and LIDAR, standard deviations cannot be compared quantitatively. Finally, vertical profiles of the turbulence intensities calculated by WindSim are verified using LIDAR measurements.

6. RESULTS

6.1 Vertical Wind Speed Profiles

Comparison of SODAR and ZephIR-LIDAR Measurements

Figure 5 shows the vertical wind speed profiles from SODAR and LIDAR measurements for the main wind direction north north-east (Bora) for different wind speed classes for Maligrad and Rudine. The data sets are normalised to 30 m (Maligrad) and 50 m (Rudine) height. The increase of the mean wind speed from 30 to 100 m is in general small for this wind direction. For wind speeds above 4 m/s the profile shape is independent to the wind speed at both studied sites. The outlier in the SODAR profile of Rudine at 40 m height is probably a result of an echo during data collection.

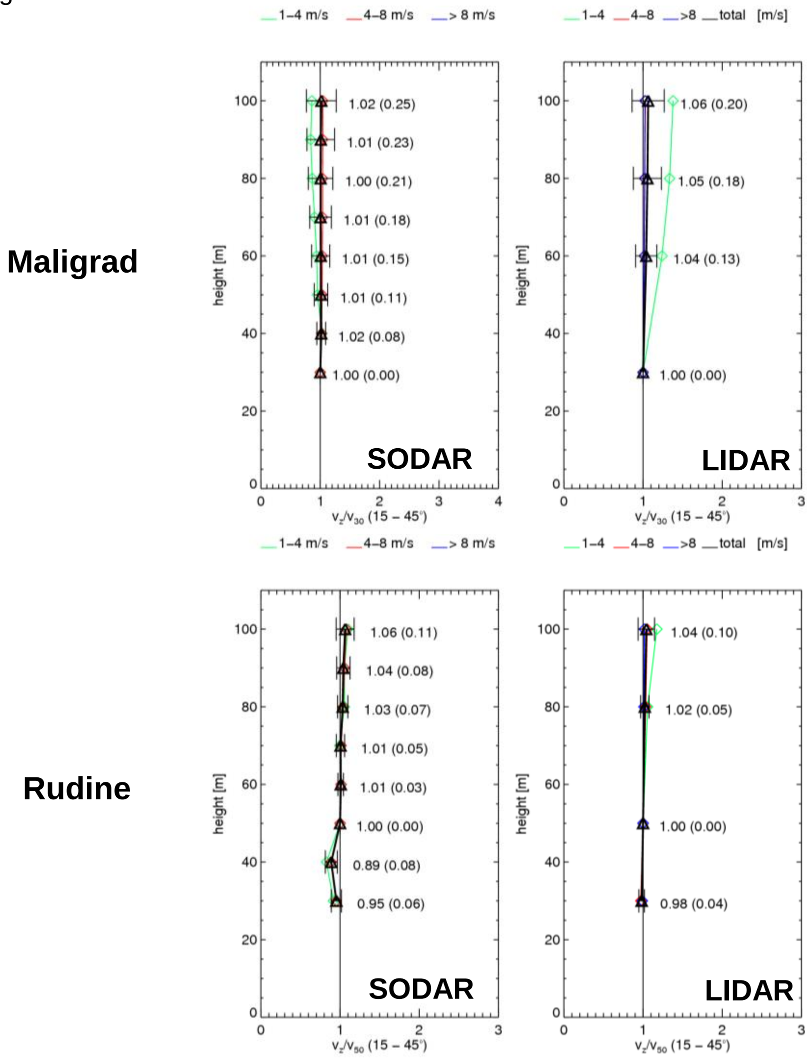

Figure 5: Vertical wind speed profiles from SODAR and ZephIR-LIDAR normalised to 30 m (top, Maligrad) and 50 m (bottom, Rudine) for the wind direction NNE (15°–45°) and for three wind speed classes; in brackets the standard deviation.

Comparison of ZephIR-LIDAR Measurements with WindSim

The vertical levels of the WindSim model output do not agree with the measurement levels of the LIDAR. For comparison reason the wind speed data of the WindSim output level from 25 m was interpolated linearly to 30 m for Maligrad. For Rudine, the 54 m level was interpolated linearly to 50 m. The model output data are normalised to these interpolated values. In Figure 6 the vertical wind speed profiles, normalised to 30 m/50 m, from LIDAR measurements and WindSim model are compared for the main wind direction north north-east (Bora). At Maligrad, the WindSim profile agrees well with the measurement. However at Rudine the WindSim result shows an increase of about 10% from 50 m to 100 m compared to the measured increase of 4% with LIDAR.

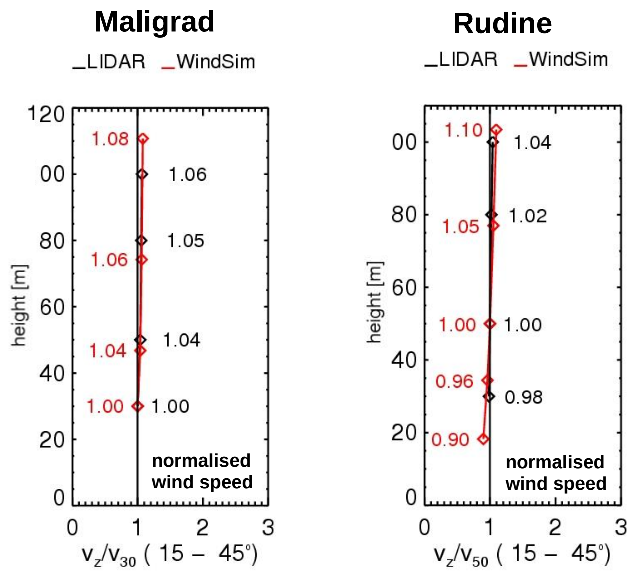

Figure 6: Comparison of vertical wind speed profiles from WindSim (red) and ZephIR-LIDAR (black) normalised to 30 m (left: Maligrad) and 50 m (right: Rudine) for the wind direction NNE (15°–45°).

6.2 Vertical Turbulence Intensity Profiles

Comparison of ZephIR-LIDAR and WindSim Turbulence Intensities

Figure 7 shows the turbulence intensities derived from LIDAR measurements and WindSim calculations for the wind direction north north-east (Bora). LIDAR turbulence intensities are calculated only for wind speeds above 4 m/s. In the WindSim output, a decrease of the turbulence intensity with height is visible while the LIDAR measurements show a constant turbulence intensity profile.

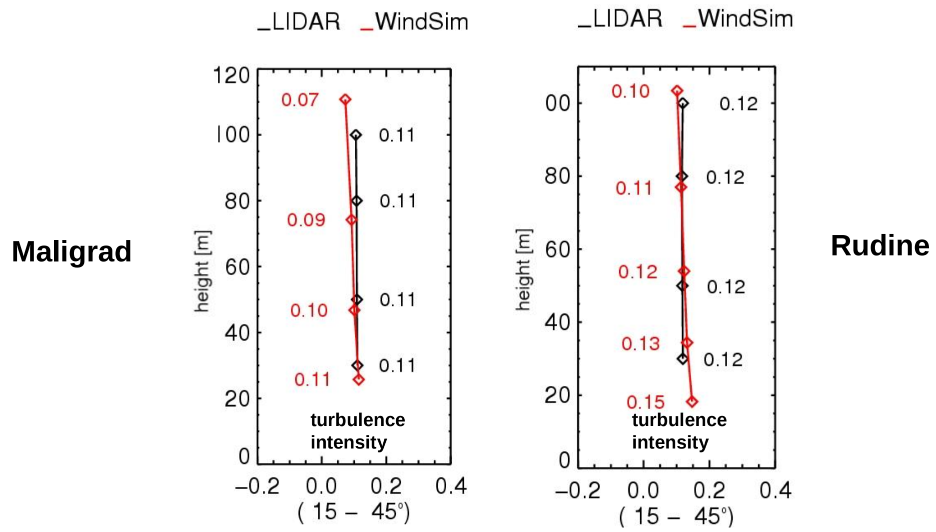

Figure 7: Vertical profiles of turbulence intensities for the wind direction NNE (15°–45°) at Maligrad (left) and Rudine (Rudine) from ZephIR-LIDAR measurements (black) and WindSim calculations (red). Turbulence intensities were calculated only for wind speeds above 4 m/s.

7. CONCLUSIONS

7.1 Bora dominated sites

- Good performance of SODAR and ZephIR-LIDAR in spite of harsh climatic conditions
- Maligrad: only one dominant wind direction
- Rudine: two dominant wind directions
- Maligrad and Rudine: nearly constant vertical wind profile up to 100 m height for sector NNE (Bora!)
- Maligrad and Rudine: nearly constant vertical turbulence intensity profile up to 100 m height for sector NNE (Bora!)
- More investigations of the temporal evolution of Bora events are needed

7.2 SODAR - LIDAR - WindSim:

- Good agreement of SODAR, LIDAR and WindSim normalised vertical wind speed profiles
- Differences in the absolute values of SODAR and LIDAR turbulence intensities (not shown in this study, see [5])
- WindSim calculations show decreasing vertical turbulence intensity profiles in contrast to the constant vertical turbulence profiles measured with SODAR and ZephIR-LIDAR
- Evaluation of turbulence intensity from SODAR and ZephIR-LIDAR data sets needs clarification

ACKNOWLEDGEMENTS

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