Turbulence intensity and high wind speeds above complex terrain: measurements and CFD-modelling

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Summary

This study presents wind measurements carried out in medium complex terrain at a site near Mostar in Bosnia and Herzegovina. Wind conditions and meteorological conditions were expected to be very extreme, in particular the so called Bora wind system showing very high wind speeds and turbulence intensities. Wind measurements were carried out with a 30m mast, a SODAR and a LIDAR. In this case study results of an 18 days period of wind measurements are analysed when data from mast, SODAR and LIDAR where available. The results from the LIDAR measurement where further used to validate simulations carried out with the CFD model WindSim.
The two motivations of the study were, first, to test the performance of SODAR and LIDAR technique under harsh meteorological conditions and second, to analyse the suitability of the site in view of the planned wind farm and determine technical requirements for the wind turbines.
Both, SODAR and LIDAR data showed good agreement and good performance with high data availability up to 100m. However, at wind speeds over 20m/s the availability from the SODAR data was strongly reduced due to high surrounding noise of the wind. Wind speed shear exhibited a rather small increase of wind speed with height especially for the prevailing wind direction NNE. Turbulence intensities calculated from SODAR and LIDAR showed biases in particular for wind speeds greater 15m/s. However, all data sets revealed almost constant turbulence intensities between 30m and 100m above ground and, in contrast to the expectations, turbulence intensities remained below class C considering IEC 61400 standard.
Modelled vertical profiles from the CFD model WindSim were compared to LIDAR measurements for twelve 30° wind direction sectors. The normalised vertical wind speed profiles of LIDAR and WindSim showed good agreement. However, in contrast to the LIDAR measurements, WindSim showed a small decrease of turbulence intensity with height.

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 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 (NNE). 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. The present case study shows results of wind measurements at Maligrad, a site near Mostar in Bosnia-Herzegovina from a period of 18 days. During these 18 days data from a 30m mast, a SODAR and a LIDAR were available. Wind speed from mast, SODAR and LIDAR at 30m and vertical wind speed profiles and turbulence intensities from SODAR and LIDAR were analysed. Finally, the performance of the CFD modeling software WindSim [2] regarding vertical profiles of wind speed and turbulence intensities was evaluated.

2. Site Description, instrumentation and measurement period

The measurement site called Maligrad was located on the high plateau approximately five kilometres east of the city of Mostar in Bosnia-Herzegovina at a height of 730m asl. (Fig 1).

Fig. 1: Map of Bosnia and Herzegovina with the wind measurement site Maligrad near Mostar.

To the east there were two hills reaching up to 880m and 1060m asl., respectively. Further east a mountain chain raised to a height of 1800m asl.. To the NNW and WSW, the terrain lowered down to around 50m asl. in Mostar.
Prevailing wind directions were NNE (Bora) and S. Wind speeds were very variable and easily reached 20m/s at 30m height. Fig. 2 shows the long term wind rose and frequency distribution at Maligrad as measured at the mast. The mean wind speed accounts to 7.2m/s at 30m above ground.

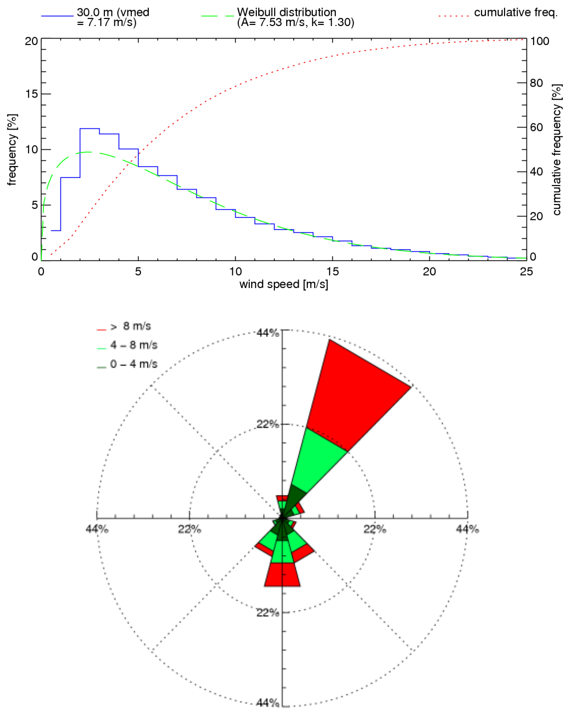

Fig. 2: Long term wind conditions at Maligrad: frequency distribution (top) and wind rose (bottom).

The 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 0.33 Hz and the averaging interval 10 minutes. The LIDAR was of ZephIR-type [3] and the five measurement levels were set to 30, 60, 80, 100 and 150 m. The measuring rate was 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. The anemometers and wind vanes were installed at 12 and 30m above ground.
SODAR and LIDAR data were available simultaneously from November 22nd to December 9th. Only the period when data from all instruments were available are considered for the present case study.

3. Wind characteristics at 30m

3.1 Wind direction and wind speed

Fig. 3 and Fig. 4 show the course of the wind direction and wind speed mast, LIDAR and SODAR at 30m. As mentioned earlier, wind directions were very pronounced either NNE or S. Wind speed where often around 10m/s (10 minute mean values) and reaching 25m/s around the 5th of December. The mean wind speed during the 18 days was 8.1m/s.

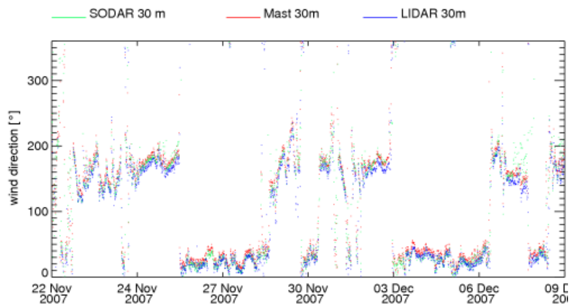

Fig. 3: Course of the wind direction from mast (red), SODAR (green) and LIDAR (blue) at 30m height during the analysed 18 days.

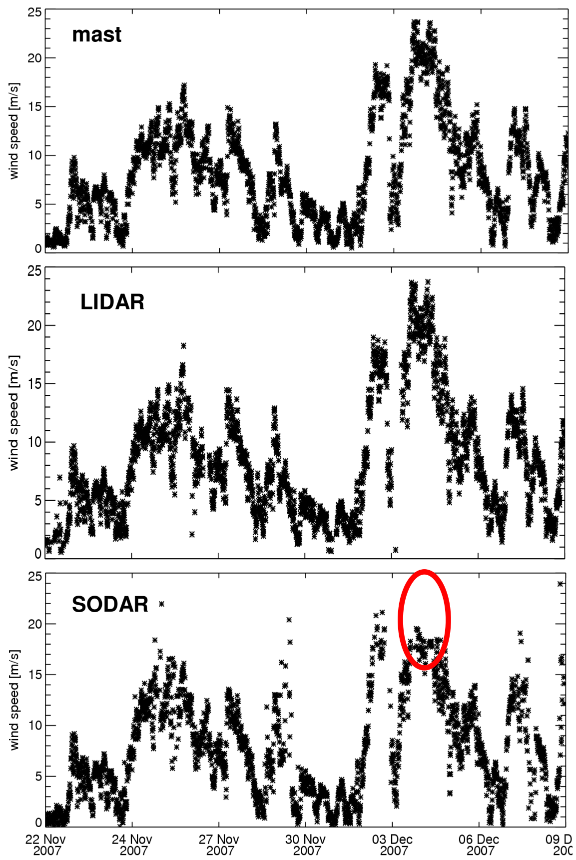

Fig. 4: Wind speed at 30m height from mast (top), LIDAR (middle) and SODAR (bottom) during the analysed 18 days. Red circle: reduced data availability from SODAR.

Wind direction and wind speed values from mast, SODAR and LIDAR agree very well. However, at wind speeds greater 20m/s the availability from the SODAR data is strongly reduced (see Fig. 4, red circle). Reliable LIDAR data were available only for wind speeds greater than 4m/s.

3.2 Turbulence intensity

Fig. 5 shows the turbulence intensity classified against the wind speed for mast, LIDAR and SODAR data. Mast and LIDAR data show almost constant turbulence intensity for wind speeds between 5 and 22m/s with a value of around 0.1. Turbulence intensities from the SODAR data are higher and show a clear increase for wind speeds greater 14m/s.

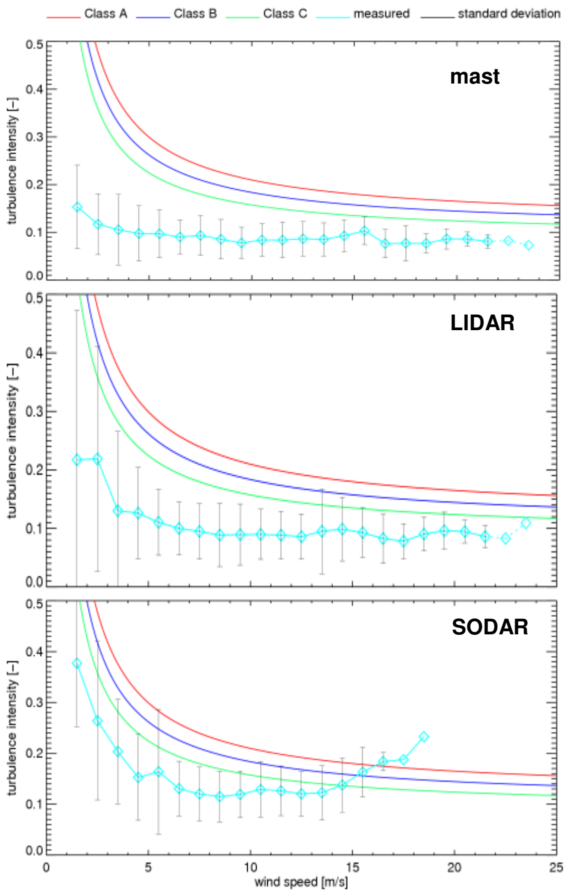

Fig. 5: Turbulence intensity classified against the wind speed from mast (top), LIDAR (middle) and SODAR (bottom)at 30m height (error bars indicate the standard deviations). Additionally the borders of class A, B and C of the IEC standard are shown.

4. Wind shear and turbulence 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 were analysed for twelve 30° wind direction sectors. Fig. 6 shows vertical wind speed profiles from SODAR and LIDAR measurements for the main wind direction NNE. The data sets are normalised to 60m height. The increase of the mean wind speed from 60 to 100m is small for the main wind directions, between 1% and 3% considering the LIDAR and between 2% and 9% considering the SODAR data.

Turbulence intensities (TI) from SODAR and LIDAR measurements are evaluated by calculating the ratio of the standard deviation wind speed (σ_U) to the mean wind speed (v) according to the following formula: $TI = \sigma_U / v$. Only wind speeds above 4 m/s are considered.

Fig. 7 shows TI from SODAR and LIDAR measurements up to 100 m height for the main wind direction sector NNE. Both instruments show an almost constant turbulence with height. The reason for the constant bias between SODAR and LIDAR data could be caused by a different data sampling rate and the lower data availability of SODAR data at high wind speeds (see Fig. 4 and Fig. 5).

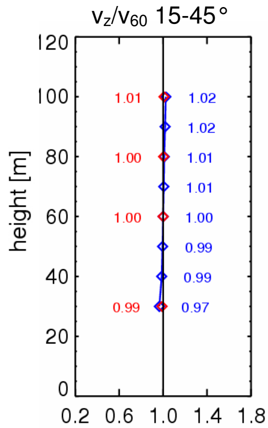

Fig. 6: Vertical wind speed profiles from SODAR (red) and LIDAR (blue) normalised to 60m for the prevailing wind direction NNE.

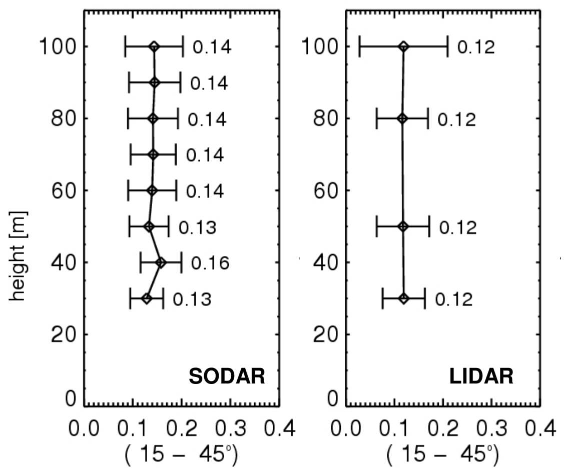

Fig. 7: Profiles of the TI from SODAR (left) and LIDAR (right) for the wind direction NNE. The bars indicate the standard deviation.

5. Validation of CFD model with LIDAR

5.1 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. The climatology was compiled from the 18 days measurement period. WindSim offers the possibility to extract vertical profiles of various parameters, like for example wind speed and turbulence intensity for each modeled height and wind direction sector. The values of the vertical WindSim profiles are only relative values which have to be scaled with a climatology.

5.2 WindSim vs LIDAR

The vertical levels of the WindSim model setup do not agree with the measurement levels of the LIDAR. For comparison reason the wind speed data of the WindSim output level from 27m were reduced to 30m and the model output data normalised to this interpolated value. In Fig. 9 vertical wind profiles normalised to 30m from LIDAR and WindSim are compared for the wind direction NNE. WindSim shows an increase of 8% from 30 to 110m, this means a slightly larger increase than seen in the LIDAR measurements. Fig. 9 shows the TI from LIDAR measurements and WindSim calculations for the sector NNE. The TI of WindSim and LIDAR agree very well in magnitude close to the ground. In contrast to the constant TI of the LIDAR WindSim shows a slightly decreasing TI with height.

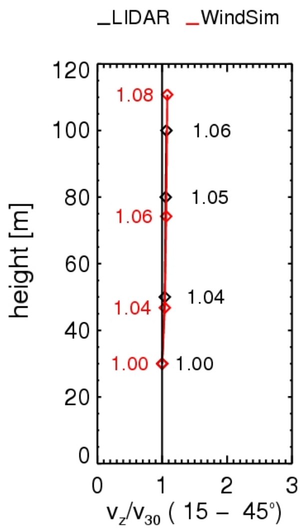

Fig. 8: Vertical wind speed profiles from WindSim (red) and LIDAR (black) normalised to 30m for the wind direction NNE.

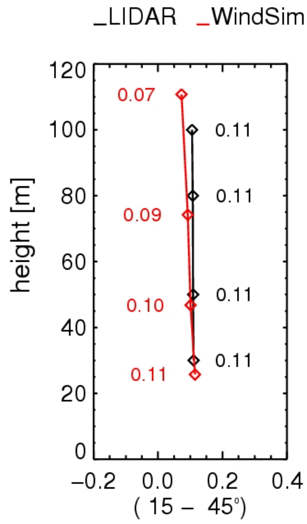

Fig. 9: TI profiles from LIDAR (black) and WindSim (red) for the wind direction NNE.

7. Summary

- Good agreement of mast, SODAR and LIDAR measurements at 30m height for wind speeds and wind directions
- SODAR: low data availability at wind speeds greater than 20m/s
- LIDAR: low data availability for wind speeds smaller 4m/s
- Nearly constant TI with increasing wind speed (not true for SODAR)
- TI remains below Class C according to IEC 61400 at 30m
- Constant vertical wind speed profile
- TI remains constant with height
- Good agreement of normalised vertical profiles from SODAR, LIDAR and WindSim

References

[1] SEEWIND, http://www.seewind.org/
[2] WindSim, http://www.windsim.com/
[3] LIDAR ZephIR, http://www.naturalpower.com/
zephir-laser-anemometer