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Editorial

Editorial for the Special Issue "Remote Sensing of Atmospheric Conditions for Wind Energy Applications"

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Abstract: This Special Issue hosts papers on aspects of remote sensing for atmospheric conditions for wind energy applications. The wind lidar technology is presented from a theoretical view on the coherent focused Doppler lidar principles. Furthermore, wind lidar for applied use for wind turbine control, wind farm wake, and gust characterizations are presented, as well as methods to reduce uncertainty when using lidar in complex terrain. Wind lidar observations are used to validate numerical model results. Wind Doppler lidar mounted on aircraft used for observing winds in hurricane conditions and Doppler radar on the ground used for very short-term wind forecasting are presented. For the offshore environment, floating lidar data processing is presented as well as an experiment with wind-profiling lidar on a ferry for model validation. Assessments of wind resources in the coastal zone using wind-profiling lidar and global wind maps using satellite data are presented.

Keywords: Doppler wind lidar; wind energy; aerosol; wind turbine; wind farm; wake; control; complex terrain; offshore

1. Introduction

Wind power is an important ingredient in the energy mix for achieving the objectives of the Paris Climate Change agreement and the Sustainable Development Goals. Next to hydropower, wind energy is the renewable energy source that contributes the most to the electricity generation worldwide with around 6%. By the end of 2018, the installed wind power capacity surpassed 600 GW with a growth of nearly 54 GW during 2018 [1].

The levelized cost of energy from wind power is competitive with that of the conventional energy sources at wind-favorable land sites. However, there is still a need to further understand and efficiently use available wind resources. This is the key motivation for research in wind energy where efforts are ongoing to lower the cost of wind energy at offshore sites, in complex terrain, and in forested areas. The wake effect within and between wind farms and wind-power forecasting are areas with increasing importance because of the need to accurately predict wind power. There is, therefore, a need for reliable, robust, and accurate measurements and datasets to further improve our understanding of the physical conditions in which wind turbines and wind farms operate and for flow model evaluation.

Nowadays, remote sensing observations are used widely in wind energy applications. During recent years, remote sensing technologies for wind have been improved in terms of accuracy and costs. The Research Infrastructure WindScanner.eu [2,3] and other new lidar advancements for the measurement of atmospheric wind and turbulence have evolved and lidars are used for research in many application fields. Site assessment based on lidar is being progressively achieved. Commercial acceptance of lidars, including floating lidars, for wind resource assessment and power performance testing is taking place.

It has been an amazingly fast development of the modern wind lidars spurred by the electro-optical developments in the telecom industry. The wind energy lidar application era started in 2003 with the testing of a continuous-wave lidar near a tall meteorological mast onshore [4]. Still, to the editors' knowledge, no entire book has yet been written on remote sensing for wind energy applications, but a compendium for education at PhD level [5] is available as well as a chapter in a book about Energy Forecasting [6].

This Special Issue, "Remote Sensing of Atmospheric Conditions for Wind Energy", from 2019 is successor to the Special Issue, "Remote Sensing for Wind Energy" [7], from 2016. There are 15 articles in the present special issue, of which 13 are on wind lidar, while in the first special issue, 9 out of 11 articles were on wind lidar. In conclusion, the wind lidar technology is dominant within remote sensing research for wind energy application at present.

In the first special issue [7], 11 articles on remote sensing for wind energy were presented. Three articles on wind lidar for wind farm wake application were given. Kumer et al. [8] focused on characterization of turbulence in the wake using lidar. Doubrowa et al. [9] focused on the uncertainty on mean winds within wind farm wake using lidar, while Dooren et al. [10] presented a methodology to reconstruct the 2D horizontal wind fields in wind farm wake based on lidars.

Along the lines of obtaining the best possible data from wind lidar, a methodology for field calibration of nacelle-based lidar was presented by Borraccino et al. [11] and a comparison of lidar data observed using three scanning lidars directed to one point versus a profiling lidar installed in complex terrain was presented by Pauscher et al. [12,13]. The latter result is important for site assessment in complex terrain.

Site assessment using lidar was also presented for other types of terrain. Floors et al. [14] presented the scanning lidar for wind resource assessment in the coastal offshore zone and Kim et al. [15] presented the use of lidar for wind assessment for high-rise building planning in urban areas.

The wind gust detection using lidar was presented by Bos et al. [16] and Vasiljević et al. [17] presented the so-called long-range WindScanner incorporating three synchronized lidar beam scanners as well as a summary of lidar field experiments.

Two studies were on satellite remote sensing. Chang et al. [18] presented on land surface temperature increase in very stable atmospheric conditions during nighttime at a large-scale wind farm in China and Hasager et al. [19] presented on ocean surface wind speeds climatology during 25 years in the South China Sea and the Atlantic North Sea.

The following Section delivers a summary of all the 15 articles published in the current special issue. Thirteen of the articles present on wind lidar. The listing of contributed articles starts with the overview article on the way towards acceptance of wind lidar within the wind energy community followed by contributions on the Doppler wind lidar technology, lidar for wind turbine control, wind turbine wake measuring using lidar, gust characterization based on lidar, and lidar for use in complex terrain. Airborne wind lidar used for measuring in hurricane conditions and ground-based Doppler radar for very short-term periods follow. Next come contributions on offshore applications including floating lidar, lidar on board a ferry, and lidars installed at the coast for characterizing coastal offshore winds. Finally, a global perspective using satellite wind data is given.

2. Overview of Contributions

Within the wind energy community, the use of wind lidar is an important new focus area with a wide spectrum of applications including site assessment, power performance testing, controls and loads, and complex flows as presented in the overview given by Clifton et al. [20]. That contribution is a status update for the International Energy Agency (IEA) Wind Task 32 called "Wind Lidar Systems for Wind Energy Deployment" that since 2012 at international level aims to identify and mitigate barriers to the adoption of lidar for wind energy applications. Already achieved are several recommended practices and expert reports that have contributed to the adoption of ground-based, nacelle-based, and floating lidar by the wind industry. It is concluded that despite progress in identifying barriers to the adoption of wind lidar for wind energy applications—and mitigating some of them—there remains a significant amount of research to be done in this field.

The coherent focused continuous-wave Doppler wind lidar fundamental equations and principles are presented in Hill [21]. The comprehensive overview in general aims at bringing forward the classical radar/lidar lessons to the broader community presently applying coherent Doppler lidars. In particular, the behavior that may be observed from a modern coherent lidar used at short ranges (e.g., in a wind tunnel) and/or with weak aerosol seeding where only very few scatterers are present in the probe volume is explained. Results on simulation of few-scatterer and multiscatterer lidar experiments are revisited and in addition, a discussion of some problems (and solutions) for Doppler-sign-insensitive lidars is presented.

Simley et al. [22] present the topic of optimizing lidars for wind turbine control. A large body of work on the optimization of lidar beam configuration via the resulting controller performance, time domain assessments of measurement accuracy, and direct frequency domain calculations of measurement coherence and measurement error is presented. Simley et al [22] present results considering beam configuration optimization for rotor effective wind speed. Various lidar types including coherent continuous wave lidar and pulsed four-beam lidar are included. Also important is the lidar data availability for the feedforward pitch controller for rotor speed regulation.

Wind turbine wake characterization based on observations using two nacelle-mounted pulsed scanning Doppler lidars at 2.5 MW wind turbines is presented by Carbajo Fuertes et al. [23]. One lidar measured the inflow while the other measured the downwind wake region. The observations were dedicated to quantify the growth rate of the wake width, the near- and far-wake extent, and the velocity deficit. The observations were compared to an analytical wake model, with good results for the velocity deficit and wake expansion. It was observed that higher turbulence intensity in the inflow resulted in shorter near-wake length and in faster recovery of the velocity deficit.

Carbajo Fuertes and Porté-Agel [24] used a virtual lidar approach to assess how accurate it appears possible to observe with lidar in the full-scale wind turbine wake. The study was based on Large-Eddy Simulation (LES) model results for a wake. The performance of a virtual lidar performing stacked step-and-stare plan position indicator (PPI) scans within the volume was calculated and the volumetric reconstruction of the winds and the accuracy were assessed for the average velocity. As an outcome, optimization of the angle resolution that minimizes the total error was provided.

Zhou [25] contributed a study using a coherent Doppler lidar data set of three hours to study wind gusts on a scale from 100 m to 1000 m. The method proposed to extract gusts from a wind field and track their movement utilizes the "peak over threshold method", Moore–Neighbor tracing algorithm, and Taylor's frozen turbulence hypothesis. The prediction model was used to estimate the impact of gusts with respect to arrival time, the probability of arrival locations, the span-wise deviation of the gusts, and the gust size. Finally, the method was used to estimate the impact of gust on the production on a hypothetical wind farm.

Mayor and Dérian [26] refuted statements in Zhou [25] that argued on impracticality of motion estimation methods to derive two-component vector wind fields from single scanning aerosol lidar data. Two image-based motion estimation methods, namely the cross-correlation and wavelet-based optical flow methods, were demonstrated to be also practical to use for wind gust detection and impact prediction on wind turbines. The characteristics and performances of the cross-correlation and wavelet-based methods were compared to a two-dimensional variational method applied to radial velocity fields from a single scanning Doppler lidar. In conclusion, the wavelet-based method and two-dimensional variational method have much in common and both are practical to use.

In complex terrain, ground-based wind-profiling lidars are used for observing the vertical wind profile but with additional uncertainty as compared to use in flat terrain. Hofsäß et al. [27] analyzed a wind lidar data set and compared to wind speeds observed at a 100 m tall meteorological mast near an escarpment of 150 m height in Germany. Three different methods to optimize the lidar data reconstruction were evaluated. It was found that a linear approach performed the best. Furthermore, the influences of the opening angle of the scanning cone and the scanning duration on data quality were analyzed in the data set. The opening angle had importance, while the scanning duration did not.

Risan et al. [28] also investigated flow in complex terrain using lidar. This study was based on a pulsed lidar measuring towards a ridge in Norway. The lidar data were used for comparison to Computational Fluid Dynamic (CFD) model results using two methods: one was a hybrid Reynolds-Averaged Navier Stokes (RANS)/Large-Eddy Simulation (LES) model, the other was a more traditional RANS model. The lidar data 10-minute mean wind speeds were very accurate compared to sonic wind data, while the 1-second turbulence had lower accuracy compared to sonic data. However, both the mean wind speed along the line of sight and the turbulence data were useful for comparing the performance of the two flow models. The first model performed well but overestimated the turbulence at the ridge, while the other model failed to estimate the turbulence over the ridge.

Zhang et al. [29] presented analysis of airborne Doppler wind lidar observation from a tropical storm called Erika (2015) in the US. The lidar was installed on a P3 Hurricane Hunter aircraft. The observations were compared with two other types of vertical profiling data sets. One was the dropsonde measurements, the other Doppler radar. Lidar and dropsonde wind speeds correlation was high and root-mean-square error and bias were low. The wind lidar enlarged the sampling size and spatial coverage of boundary layer winds, and was found valuable for real-time intensity forecasts and for understanding boundary layer structure and dynamics, and can be used for offshore wind energy applications. The lidar operates best in rain-free and low-rain conditions while the radar performs better in rain. Thus the lidar and radar are complementary in observing winds.

Valldecabres et al. [30] investigated Dual-Doppler radar data from two radars located on the coastline and observing several kilometers offshore covering an offshore wind farm in the North Sea. The radar-based wind data are analyzed to produce very short-term wind power forecasts, around five minutes ahead. The wind variations observed upstream are used in an advection Lagrangian persistence technique to forecast the density of wind speeds at the target turbines. The radar-based forecasts outperformed the persistence and climatology benchmarks when predicting the power generated. The radar-based forecasts were corrected for induction effects. It is important that a sufficiently large spatial coverage of the inflow for a turbine is observed to produce a reliable density forecast.

The winds offshore in the coastal zone were investigated using two vertical profiling pulsed lidars by Shimada et al. [31]. The instruments were located at the coast and 400 m out, mounted on a long pier in Japan. Six months of observations were available for the analysis that focused on the effect of fetch for winds blowing from land to sea. Also, the winds from the ocean towards land were analyzed. The effect of fetch at several levels up to 200 m were quantified and a strong gradient was noted at the lower heights but less pronounced at higher levels. The data set would be valuable for comparison to model results of the coastal wind climate.

Gottschall et al. [32] also investigated offshore coastal winds using lidar observations. The study was based on a pulsed vertical profiling lidar installed on board a ferry that daily passes a distance of several hundreds of kilometers in the Baltic Sea. The lidar data were motion-corrected using relevant motion measurements. The data availability was good and observations reached as high as 250 m. The lidar data were subsequently used for comparison to a mesoscale numerical weather prediction model, and the correlation of wind speeds was good. The ferry-based lidar data are from a trajectory so the collocation of lidar data and model results prior to comparison had to be done.

Gutiérrez-Antuñano et al. [33] focused on motion correction of data from a floating vertical profiling coherent continuous wave lidar observing in the Netherlands. The comparison of the observations from the floating lidar uncorrected and corrected were done to sonic anemometer measurements and data from a fixed vertical wind-profiling lidar nearby during 60 days of observations. Both 10-minute mean wind speed and turbulence were analyzed. The proposed motion correction method combines a software-based velocity-azimuth display and motion simulator and a statistical recursive procedure. It assumes simple-harmonic motional conditions such that only one motional amplitude and period is needed and wind direction is neglected. The comparison was good for both wind speed and turbulence in particular comparing lidar to lidar.

Guo et al. [34] analyzed the archive of satellite ocean wind speed products based on two scatterometers, ASCAT and QuikSCAT, and one passive polarimetric microwave, WindSat, satellite. Firstly, the wind products were compared to ocean buoy data during several years and differences in the biases between the products and buoy winds were noted. Next, the collections of data sets were combined and mean wind speed was calculated in all grid cells. A simple extrapolation to 100 m was done and wind power density was estimated.

3. Conclusions

This Special Issue highlights the use of remote sensing for atmospheric conditions for wind energy research. Wind lidar is the dominant remote sensing method giving new opportunities for observing winds and turbulence and the wind lidar technology is applied broadly. The lidar observations prove useful for validating models as well as for characterizing the boundary layer structure and dynamics. This is particularly valuable in complex terrain and offshore. The flow near wind turbines and wind farms influenced by the operating wind turbines (i.e., wake and inflow) is observed well by remote sensing and remote sensing data are useful for forecasting the power at very short time scales.

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