EROSION

D3.1 Lidar tested versus disdrometer

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Preface

This report presents the prototype lidar functionality for rain detection tested next to disdrometers in the EROSION project.

The project is funded by Innovation Fund Denmark and project partners. The project period is from April 1st, 2017 to March 31st, 2020 (3 years).

The aim of the project **EROSION – Wind turbine blade erosion: Reducing the largest uncertainties** is to create knowledge and methods to avoid blade erosion caused by rain and hail. The hypothesis is that by reducing the tip speed of the blades, where rain and hail cause severe blade erosion, a significant extension of blade lifetime can be obtained with reduced maintenance cost and negligible loss of production.

The key objective of EROSION is to enable longer lifetime of wind turbine blades at multi-MW machines. To achieve the objective the project work will include testing of specimen in a rain erosion tester and investigation and analysis of damage on leading edges of blades. Furthermore, the rain in real atmosphere will be investigated from ground-based instruments (disdrometers) and modelling of rain based on rain radar data. Finally a new prototype instrument will be developed in order to measure rain at wind turbines for making decision on control, to set 'erosion safe mode' with regulation of turbines. Much longer lifetime of wind turbine blades and reduced operation and maintenance costs are expected.

Project web-site is http://www.rain-erosion.dk/

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Executive summary

This report describes the concept and field test results of prototype devices for precipitation monitoring in the EROSION project funded by Innovation Fund Denmark and project partners. The project period is from April 1st, 2017 to March 31st, 2020 (3 years).

For the completion of the project there is a need for an instrument that can measure rain at wind turbines for making decision on control, to set ‘erosion safe mode’ with regulation of turbines. Much longer lifetime of wind turbine blades and reduced operation and maintenance costs are expected.

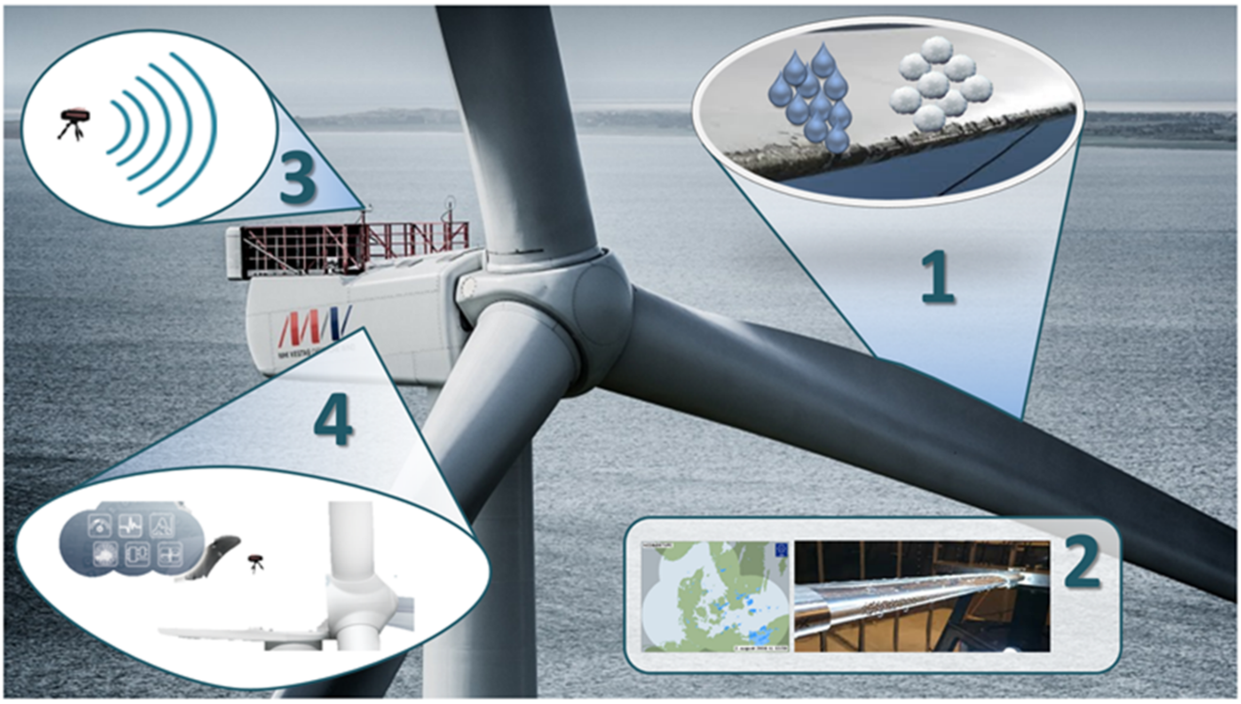
The ultimate goal of the sensor development within the EROSION project is a sensor for in-situ warning of rain erosion events which does not require high accuracy in the absolute rain drop distributions measured but rather an indication of the rain erosion potential which is equally valuable regardless of any unknown scaling function. This purpose relaxes the requirements for a local sensor substantially and the outlined novel rain detection functionality for wind lidars has with respect to that goal shown successful results during a field inter-comparison campaign at the Risø test site for wind turbines with a co-located optical Parsivel^2 disdrometer and three radar-based disdrometer instruments called WS100.

The lidar technology is costly but if already used the additional cost for providing a rain-erosion safe mode signal would be low. However, for a dedicated sensor solution the piezo-electric approach has the potential for becoming an extremely cheap solution. Initial hardware prototyping and laboratory testing has already been achieved within the EROSION project as a first step on the long way towards a mature rugged field sensor for rain erosion on wind turbines.

1 Introduction

1.1EROSION research hypothesis

In the EROSION project the research hypothesis is that large rain drops cause significant erosion at the leading edges of wind turbine blades. Furthermore, it is assumed that leading edge erosion can be prevented by slowing down turbines during heavy rain. The project aims to test erosion safe mode control using on site rain instruments at wind turbines. The rain erosion test data will be used to guide the necessary control strategy. The research hypothesis is sketched in Figure 1.



1. **Research hypothesis:** Erosion damage is mainly generated during heavy precipitation (big drops of rain or hail), which occurs in a very little fraction of the turbines operation time. By reducing the tip speed of the blades in these few hours a significant extension of the leading edge lifetime can be obtained with negligible loss of production.

2. **Methodology:** Define rain and hail erosion classes to quantify leading edge blade in-field and in lab testing. Correlations between rain intensity, droplet size, impact speed, materials properties, etc. will be established.

3. **Measurement Device:** Low-cost prototype for precipitation measurement on site and real time warning device enabling modern control of wind turbines.

4. **Erosion safe mode:** A safe mode control based on the erosion classes to control the wind turbine, reducing the tip speed under severe conditions – preventing aerodynamic degradation and reducing maintenance costs.

Figure 1. Sketch of the research hypothesis in the EROSION project.

1.2 Concepts for an in-situ precipitation device

Disdrometers measure the rain drop size distribution and fall velocity. Within the EROSION project disdrometers are used for obtaining background knowledge (see Deliverable D1.1). Although several types of disdrometers exist as reviewed in (Kathiravelu, Lucke, & Nichols, 2016), they are not suitable for installation on a wind turbine. Therefore, a new concept is needed. Within the EROSION project, development and field test of a novel lidar-based disdrometer concept has been undertaken as well as initial prototyping and laboratory testing of a piezo-electric disdrometer concept pursued by DTU Wind Energy colleague Søren Ott.

By coincidence, an uncorrelated company called OTT has in addition offered the EROSION project to test a brand new short-range radar-based disdrometer called WS100. This report presents the lidar disdrometer concept and some results from the field test performed concurrently with co-located WS100 and Parsivel^2 disdrometers at the Risø test site for wind turbines.

2. Lidar-based precipitation sensor

2.1 Aim to achieve

The original aim of the activities was to develop and test an innovative rain lidar concept using demonstrated wind lidar remote sensing instruments such as SpinnerLidar, WindScanner, and Lidics all developed at DTU in combination with turbine blade or nacelle installed piezo-electric sensors. During rainfall the rain lidar should be operated to record combined Doppler shifts from droplets fall velocity and backscatter signal intensity.

Figure 2. Turbine-mounted SpinnerLidar and blade-mounted Lidics developed in previous DTU-lead projects. The novel precipitation detection lidars are utilizing existing hardware but with novel processing algorithms.

2.2 The Doppler lidar principle

A remote sensing Doppler lidar (LIght Detection And Ranging) instrument is similar to a radar but operates with laser light, although invisible for the naked eye at a wavelength of about 1.5µm in the more eye-safe range of the near-infrared spectral region. The coherent Doppler lidar emits into the air a beam of coherent light that is scattered by naturally existing aerosols and droplets in the air and to a small fraction reflected back to an optical detector inside the lidar that detects both a fraction of the emitted light and the light returned from the air. Thanks to the Doppler Effect, the frequency of the light reflected by the moving particles in the air gets a slight frequency shift. This frequency shift is proportional to the speed of the air with a proportionality constant only dependent on the speed of light and the wavelength of the light. The frequency shift is detected as the beating frequency between the emitted and backscattered light and is for light with a wavelength of 1565 nm about 1.28 MHz per 1 m/s. The frequency shift can easily be identified by acquiring the detected light at a sampling rate of about 100 MHz or more followed by a Fourier transformation producing Doppler spectra as illustrated in Figure 3.

For standard lidar-based wind measurements, it is only the location of the Doppler spectrum peak along the frequency/velocity axis that is of interest. The shape of the spectrum is not utilized for wind measurements and multiple peaks from both the aerosols moving with the wind and falling water drops are merely a cause for outliers in the estimated wind speed time series that requires filtering. However, the proposed precipitation lidar utilizes the extra Doppler spectral intensity information that hitherto has not been used.

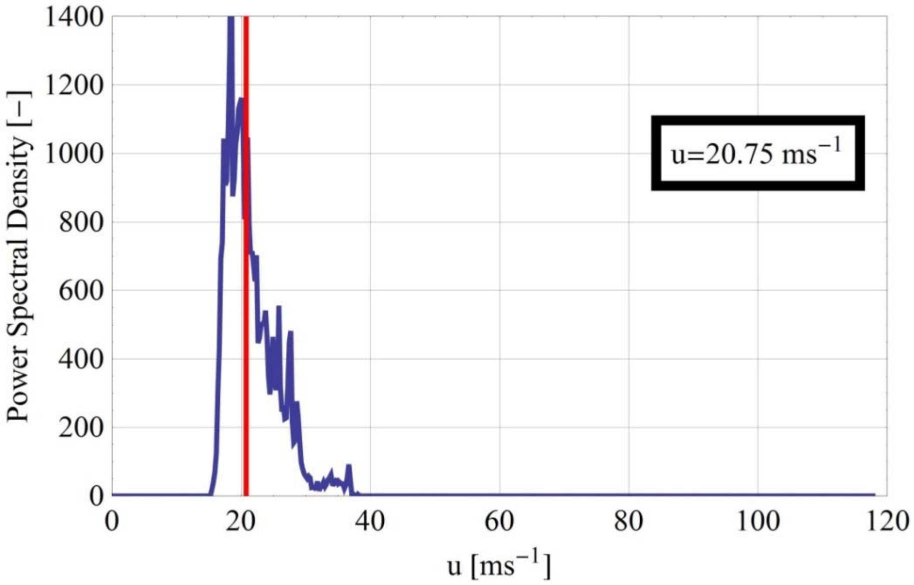


Figure 3. Example of lidar-measured joint velocity and area spectrum of 0.2 mm ceramic particles.

It is only the velocity component of the moving atmosphere or moving rain droplets along the laser beam that is detected so if the direction of the velocity is unknown, three line-of-sight measurements are needed in order to fully characterize the three components of the wind field which is routinely done by the DTU-developed WindScanners (www.windscanner.eu).

2.3 Lidar precipitation terminal fall velocity sensor

The ranging in a Doppler lidar can either be achieved by sending out pulsed light and detecting the return signal as function of time or by using continuous-wave light that is focused at various locations along the line-of-sight. The idea for the local lidar-based precipitation sensor is to use continuous-wave laser light as is done in existing Doppler lidars such as the commercially available British ZephIR lidar and the Danish Windar Photonics lidar as well as the DTU Wind Energy developed SpinnerLidar, short-range WindScanners and Lidics. In such a configuration, the signal detected from locations around the point where the light is focused will be sampled with an along-the-beam Lorentzian weighting function which becomes wider the further away the beam is focused as illustrated in Figure 4.

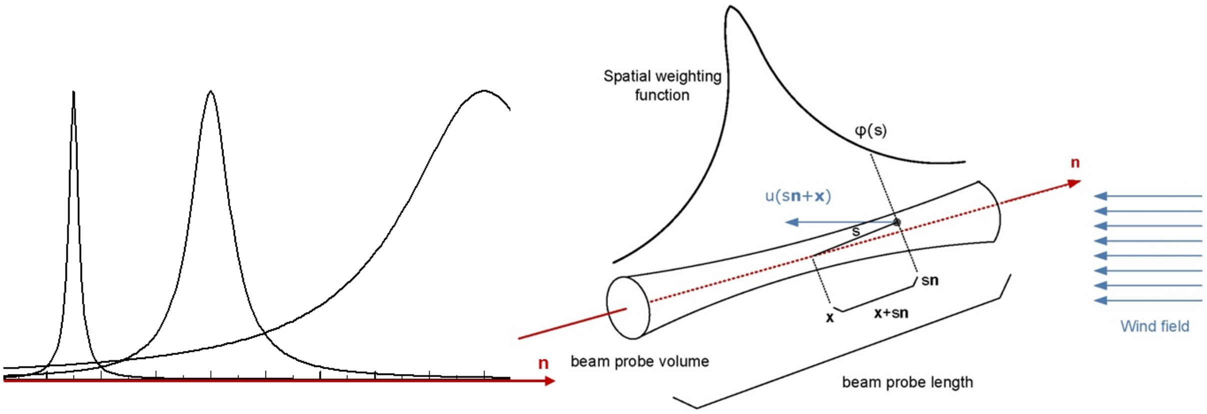


Figure 4. The sampling volume profile along the beam increases quadratically with the distance to the point where the beam is focused.

The average Doppler spectrum will provide the joint velocity and droplet light backscattering distribution overlaid on top of the Doppler spectrum from the wind which needs to be de-convolved. One procedure for doing this for the case of large lidar sampling volumes was outlined in a recent paper (Aoki, Iwai, Nakagawa, Ishii, & Mizutani, 2016). However, the case investigated within the EROSION project has small sampling volumes, in the order of a decimeter, providing on short time scale distinct sharp droplet-induced spectral peaks allowing for an alternative novel analysis method further outlined in Chapter 3.

The droplet terminal fall velocity is determined from the lidar measurements and the droplet size distribution can in principle be obtained from a pre-established relation between terminal droplet fall velocity and droplet size as can be seen in Figure 5 originating from (van Dijk, Bruijnzeel, & Rosewell, 2002).

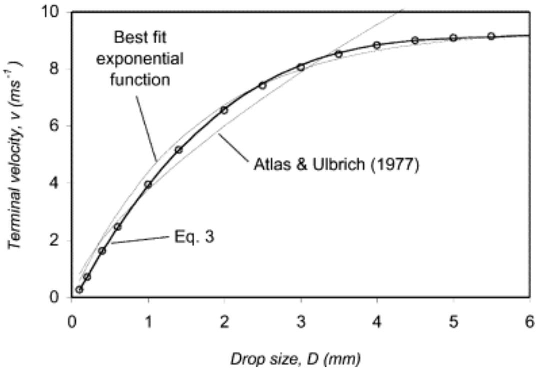


Figure 5. The relationship between raindrop size and terminal fall velocity based on data from Gunn and Kinzer as presented in (van Dijk, Bruijnzeel, & Rosewell, 2002).

2.3 Lidar precipitation velocity and droplet size sensor

The lidar can in principle not only provide the droplet terminal fall velocity which can be related to the droplet size distribution as discussed in section 2.2 but actually also provide the true droplet size distribution. However, this is less straight-forward since the cross-section of the lidar laser beam varies with the position along the line-of-sight. Thus, the backscattering from a smaller droplet close to the focus point could be similar to the backscattering from a larger drop further away from the focus point. For individual drops this is a fundamental limitation. However, on average distributions, relevant parameters could potentially be retrieved by a proper de-convolution of the sampling profile from the backscattering distribution. The general understanding of this ambiguity needs further investigation beyond the scope of the current investigation. However, the influence of this is less for tightly focused measurement beams at short-range as used in the present study.

3. Experiment set-up and analysis procedures

3.1 Experiment set-up

The EROSION project has benefited from the installation of three short-range WindScanner lidars measuring in one location for an extended period of time in a parallel project called TrueWind for field calibration of cup anemometers at the DTU Risø campus as seen in Figure 6. In the close vicinity of this test stand, one optical Parsivel^2 disdrometer as well as three radar-based OTT WS100 disdrometers have been mounted for comparisons with the precipitation results obtained from lidar Doppler spectra.

Figure 6. The test site at DTU Risø Campus with three WindScanner lidars measuring in the vicinity of the Parsivel^2 disdrometer and the three WS100 radar-based disdrometers.

3.2 Time evolution of Doppler spectra

Doppler spectra from the three lidars were recorded at 20 Hz and in Figure 7 a 10 minute period of 12000 such spectra are displayed for an occasion without rain. The y-axis represents the Doppler velocity along the line-of-sight of the lidar beam and the color represents the strength of the Doppler signal. It can be seen that the peak of the consecutive spectra follow a brighter blue continuous trace corresponding to the wind speed component along the measurement beam.

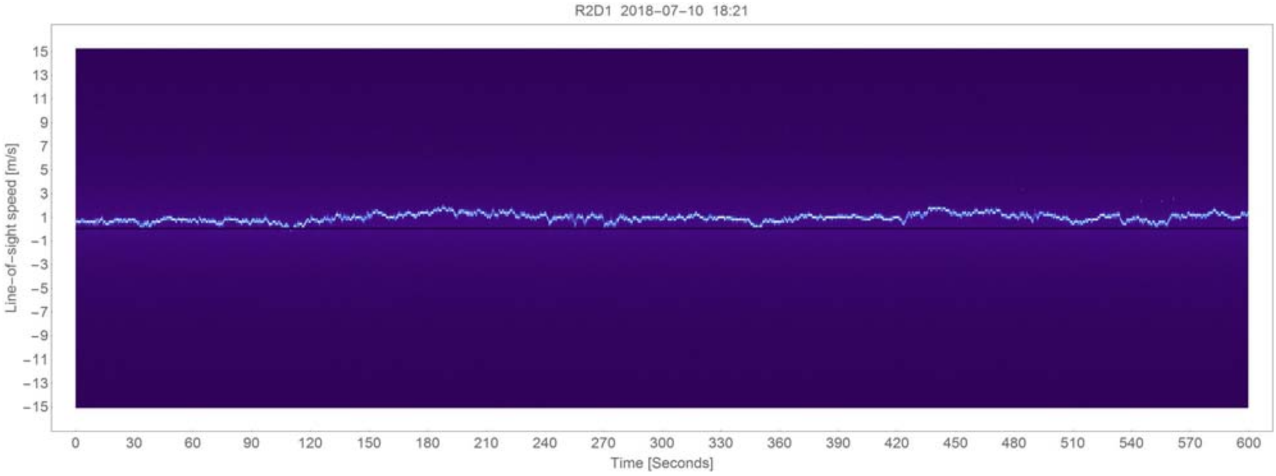


Figure 7. Time evolution of lidar Doppler spectra for a 10 minute long period without rain.

In Figure 8 a similar Doppler spectra time trace as seen in Figure 7 is provided. However, this time the Doppler spectra were recorded half an hour later during a rain shower. It can clearly be seen that a band of intermittent bright blue dots are present above the continuous bright blue trace corresponding to the wind speed component along the measurement beam. The intermittent spectral peaks are in this case the enhanced backscattering from rain droplets within the lidar measurement volume.

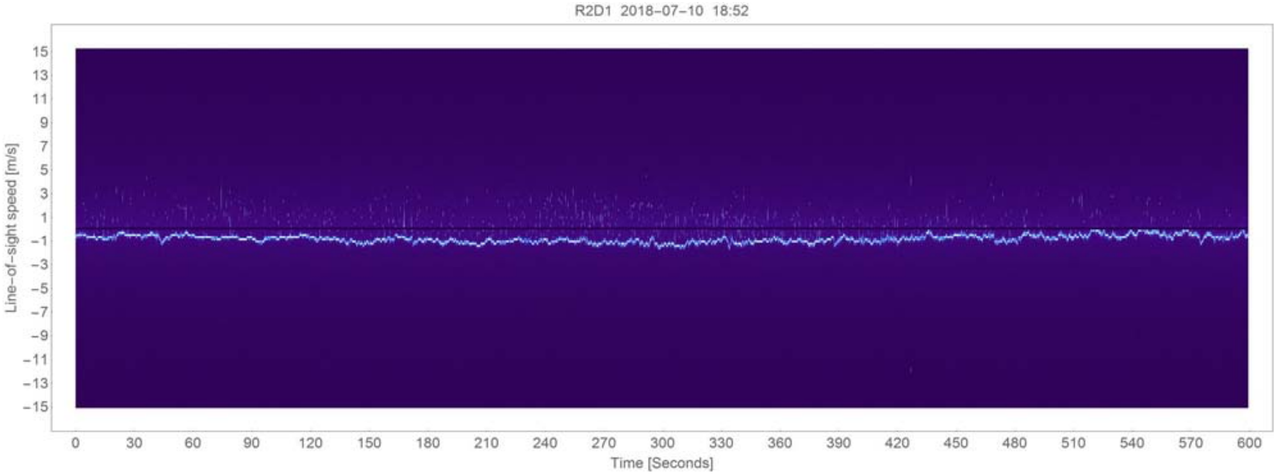


Figure 8. Time evolution of lidar Doppler spectra for a 10 minute long period with rain.

3.3 Rain relative speed spectra

As a first step in quantifying rain from wind lidar Doppler spectra, we have calculated what we call rain relative speed spectra under the assumption that the rain droplets follow the wind flow except from an additional vertical gravity-induced speed component of the drops. These relative speed spectra have been obtained by searching for multiple peaks in each individual Doppler spectrum obtained at a rate of 20 Hz. The result for each spectrum is a list of one or more peak locations on the line-of-sight speed axis.

For lidar beams pointing upwards the Doppler spectra peak having the lowest speed is generally assumed to be the wind speed and the peaks associated with higher speeds are assumed to originate from droplets or other larger particles with an additional gravity-induced fall velocity. We have subtracted the lowest of the peak speeds in each spectrum from all the peak speeds in the same spectrum, which results in spectra with speeds relative to the simultaneous wind speed.

Such rain relative speed spectra obtained by the procedure described are provided in Figure 9 for the Doppler spectra time traces presented in Figure 7 and Figure 8, respectively. Due to the procedure used, there will obviously be one count at zero relative velocity for each spectrum, which for the experimental settings used sums up to 12000 counts during a 10-minute period. In the histogram in Figure 9 only the lower fraction of those many counts can be seen since the y-axis is cut at 500 counts in order to make the interesting features visible.

As always in signal processing, there is a trade-off between detecting noise and rejecting true signals and this is also the case here regarding peak detection and the peak-finding criteria can be further refined and optimized by analysis of extended validation measurements under various turbulence and rain conditions.

Various avenues can be followed in order to quantify rain-related parameters from the rain relative speed spectra. For the subsequently presented results in this report, the number of counts in a rain relative speed spectrum except from the counts in the first bin has been integrated to form a measure of the total number of counts detected.

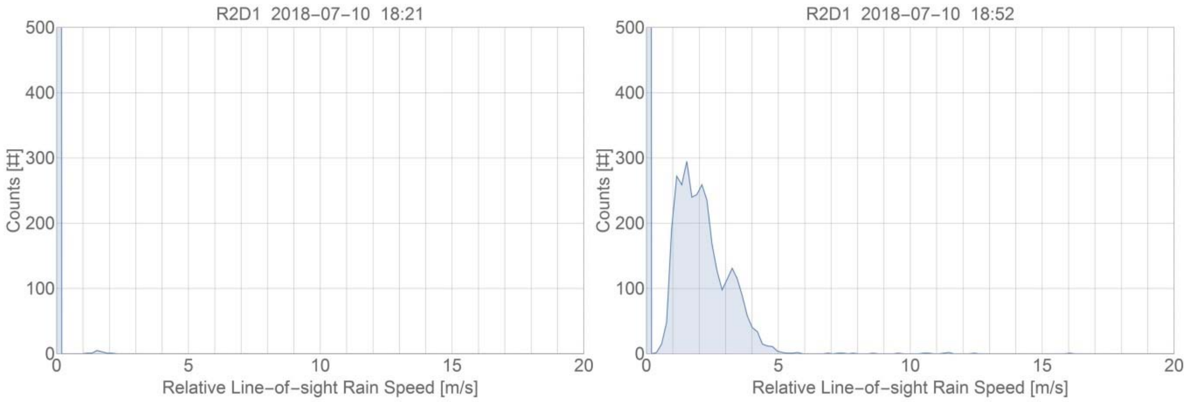


Figure 9. Rain relative speed spectra for the two corresponding Doppler spectra time traces presented in Figure 7 and Figure 8, respectively. The left figure originates from a 10-minute period without rain and the right figure originates from a 10-minute period during a rain shower.

4. The radar-based disdrometer

In addition to the DTU Wind Energy developed lidar-based concept, a novel commercially available radar-based disdrometer concept has been tested in the form of the so-called OTT Lufft WS100-UMB – Radar Precipitation Sensor. It is based on a radar reflection method to measure velocity on hydrometeors by a 24-GHz-Doppler radar (https://www.lufft.com/products/precipitation-sensors-287/ws100-radar-precipitation-sensor-smart-disdrometer-2361/). Figure 10 shows the instrument.

Figure 10. WS100 Radar Precipitation Sensor / Smart Disdrometer. Source: ***https://www.lufft.com/products/precipitation-sensors-287/ws100-radar-precipitation-sensor-smart-disdrometer-2361/productAction/outputAsPdf/***

5. Field inter-comparison results

Although the field validation campaign suffered from an extremely dry period during July 2018 when all instruments were operational, some rain events of various intensities were captured. As mentioned, one Parsivel^2 disdrometer as well as three WS100 disdrometers were co-located with the three wind lidars. In Figure 11 two of the rainy days with different rain intensities are shown. The top part shows the results from the novel lidar methodology, the middle part shows results from the WS100 radar-based disdrometer and the lower part presents the optical Parsivel^2 disdrometer results. The scales have been selected such that they just cover the magnitude of the heavy rain event on July 28th for each type of instrument and have then been kept constant between the dates in order to facilitate comparison of relative signal strengths between the different rain events for the different instruments.

The three different curves in the lidar and radar plots respectively represent the three instruments of the same type. Some variability between those for the lidars can be seen compared to those from the radar-based disdrometers, which could be due to local variability of the rain in the vicinity of the meteorology mast as well as influence from noise indicating an algorithm optimization potential as well as possibly a hardware optimization since no rain removal device for the window in the optical path was implemented. For the measurements on July 28th it should be noted that the data collection system was turned on just on the onset of the rain shower.

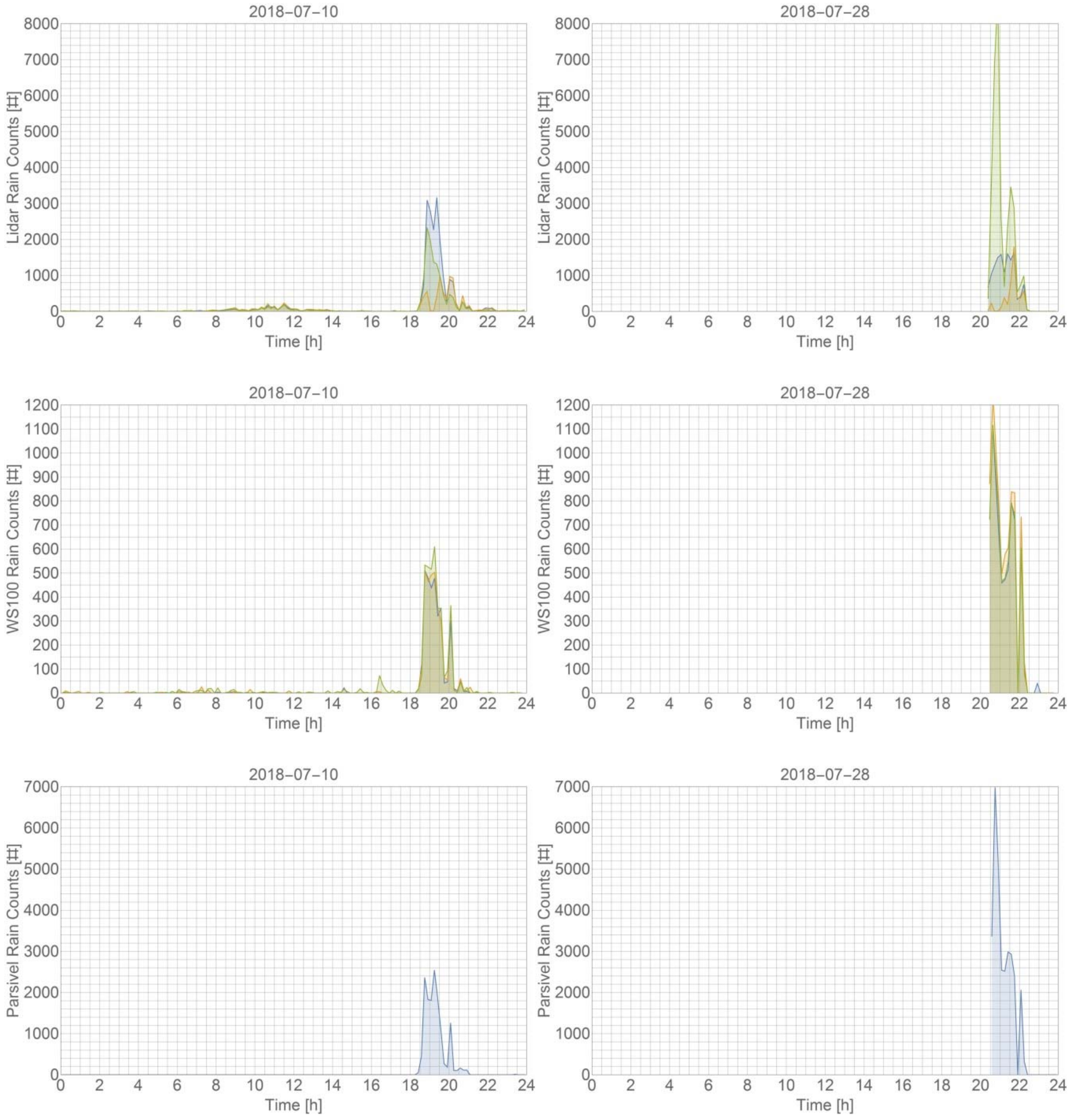


Figure 11. Results from two rainy days measured on the *top row* by the novel lidar methodology, on the *middle row* by the radar-based WS100 disdrometer and on the *lower row* by the optical Parsivel2 disdrometer. For the lidar and the radar-based WS100 disdrometer graphs, results from the three replicas of each type of instrument, compare Figure 6, are represented using different colors.

6. Summary and conclusions

The ultimate goal of the sensor development within the EROSION project is a sensor for in-situ warning of rain erosion events which does not require high accuracy in the absolute rain drop distributions measured but rather an indication of the rain erosion potential which is equally valuable regardless of any unknown scaling function. This purpose relaxes the requirements for a local sensor substantially and the outlined novel rain detection functionality for wind lidars has with respect to that goal shown successful results as well as the radar-based instrument during the field campaign at the Risø test site for wind turbines.

The lidar technology is costly but if already used, the additional cost for providing a rain-erosion safe mode signal would be low. However, for a dedicated sensor solution the piezo-electric approach has the potential for becoming an extremely cheap solution. Initial hardware prototyping and laboratory testing has already been achieved within the EROSION project as a first step on the long way towards a mature rugged field sensor.

Although the lidar and piezo-electric disdrometer methodology has long-term prospects for development into useful low-marginal-cost add-on in cases where a lidar already is installed on a turbine for other purposes, the main solution highway to follow in the subsequent tasks of the EROSION project has been decided to be based on the WS100 instrument which is available at a lower project deployment cost than the lidar solution currently available.

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