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Atmospheric Measurement Techniques Discussions

The COTUR project: Remote sensing of offshore turbulence for wind energy application

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Abstract.

The paper presents the measurement strategy and dataset collected during the COTUR (COherence of TURbulence with lidars) campaign. This field experiment took place from February 2019 to April 2020 on the southwestern coast of Norway. The coherence quantifies the spatial correlation of eddies and is little known in the marine atmospheric boundary layer. The study was motivated by the need to better characterize the lateral coherence, which partly governs the dynamic wind load on multi-megawatt offshore wind turbines. During the COTUR campaign, the coherence was studied using land-based remote sensing technology. The instrument setup consisted of three long-range scanning Doppler wind lidars, one Doppler wind lidar profiler and one passive microwave radiometer. Both the WindScanner software and Lidar Planner software were used jointly to simultaneously orient the three scanner heads into the mean wind direction, which was provided by the lidar wind profiler. The radiometer instrument complemented these measurements by providing temperature and humidity profiles in the atmospheric boundary layer. The preliminary results show an undocumented variation of the lateral coherence with the distance from the coast. The scanning beams were pointed slightly upwards to record turbulence characteristics both within and above the surface layer, providing further insight on the applicability of surface-layer scaling to model the turbulent wind load on offshore wind turbines.

1 Introduction

The coherence of turbulence is a measure for the spatial correlation of the velocity fluctuations in the incoming wind field (Panofsky and McCormick, 1954) and is one of the key parameters for the estimation of wind turbine loads. In wind engineering, the modelling of the coherence is required to design structures with dimensions much larger than the size of the eddies (Davenport, 1962), such as long-span bridges, high-rise buildings, but also wind turbines. The continuously increasing rotor diameter of state-of-the-art wind turbines has motivated the growing interest toward an improved characterization of the coherence (e.g.

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Table 1. List of offshore wind farms with commissioned wind turbines having a rotor diameter larger than $150\,\mathrm{m}$.

Farm name	Location	Diameter (m)	Year
Arkona	Germany	154	2019
Beatrice	United Kingdom	154	2019
Borkum Riffgrund 2	Germany	164	2019
Hohe See	Germany	154	2019
Horns Rev 3	Denmark	164	2019
Hornsea 1	United Kingdom	154	2019
Merkur	Germany	150	2019
Rentel	Belgium	154	2019
Galloper	United Kingdom	154	2018
Race Bank	United Kingdom	154	2018
Burbo Bank Ext.	United Kingdom	164	2017
Dudgeon	United Kingdom	154	2017
Gode Wind	Germany	154	2017
Veja Mate	Germany	154	2017
Westermost Rough	United Kingdom	154	2015

Saranyasoontorn et al., 2004; Kelley et al., 2005; Bachynski and Eliassen, 2019; Doubrawa et al., 2019). Commissioned offshore wind turbines with a rotor diameter larger than $150\,\mathrm{m}$ have been deployed since 2015 and their number has been increasing (table 1). Even larger diameters are currently developed, such as the GE's Haliade-X wind turbine, which has a diameter of $220\,\mathrm{m}$. Such dimensions challenge the traditional modelling of the coherence, which relies often on onshore measurements from meteorological masts, typically not covering the full spatial extent of modern wind turbines. The poor data coverage at altitudes relevant to offshore wind turbines, i.e. from $50\,\mathrm{m}$ to $200\,\mathrm{m}$ above sea level (asl), has been identified as one major challenge for wind energy research (Veers et al., 2019).

For wind turbine design, the spatial correlation of eddies needs to be assessed both in terms of vertical and lateral coherence. The lateral coherence refers herein to the coherence of any of the three wind velocity components, in the horizontal plane, in the crosswind direction. The vertical coherence refers to vertical separations. There exist hardly any detailed study of the lateral coherence in the Marine Atmospheric Boundary Layer (MABL), whereas it has been studied onshore since the 1970s using linear arrays of met-masts (e.g. Pielke and Panofsky, 1970; Ropelewski et al., 1973; Perry et al., 1978; Peng et al., 2018). Such an approach is not convenient for the MABL because of the prohibitive cost of installing tall met-masts offshore. Anemometers mounted on bridge decks crossing water spreads have been used in the past (e.g. Kristensen and Jensen, 1979; Toriumi et al., 2000; Cheynet et al., 2019), but the measurements were inherently affected by the local topography or by the bridge girder.

The rising popularity of affordable commercial Doppler wind lidars (DWL) has opened up a new opportunity to study the lateral coherence of offshore wind. The possibility to use DWLs to study the coherence was already mentioned at the end of the 1980s by Kristensen et al. (1989). However, the first full-scale measurements were conducted onshore during the 2000s only (e.g. Lothon et al., 2006). For the past ten years, multiple synchronized lidars have been deployed during pilot campaigns to

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study the lateral coherence (Cheynet et al., 2016a, 2017b; Letson et al., 2019) but none of them attempted to capture it in an offshore environment. During the OBLEX-F1 campaign, the coherence was assessed above the sea using a single pulsed DWL and plan-position indicator sector scans (Cheynet et al., 2016b). The use of a single scanning lidar means that a relatively low sampling frequency, around $0.20\,\mathrm{Hz}$, was used and that the scanning beams were not truly parallel to the mean wind direction.

The present study introduces a multi-lidar setup to investigate the characteristics of offshore wind coherence from DWLs located onshore. The instruments were deployed between 2019 and 2020, as part of the COTUR campaign (COherence of TURbulence with lidars). COTUR was a joint research project developed and carried out by NORCE, the University of Bergen, the University of Stavanger and Equinor. The main objective of COTUR was to assess how multiple synchronized DWLs can be utilized to characterize the lateral coherence of turbulence above the sea, at altitudes close to the hub height of large offshore wind turbines. Therefore, the measurement campaign may improve the understanding of the second-order structure of turbulence above the ocean. In this regard, the project complements recent studies of offshore wind measurement from remote sensing instruments on land (e.g. Floors et al., 2016).

The project utilized three synchronized long-range Doppler scanning lidar systems deployed on the seaside to study the lateral coherence of the wind above the ocean, at a distance up to $2\,\mathrm{km}$ from the coast. The scanning beams of the lidars were aligned automatically every hour into the mean wind, using the wind direction measured by an additionally deployed Doppler lidar wind profiler. To supplement the lidar measurements, a passive microwave radiometer was deployed to record vertical temperature and humidity profiles thorough the boundary layer. During the last two weeks of the campaign, two masts equipped with one 3D ultrasonic anemometer each were deployed north to the measurement site to validate the ability of the lidar setup to capture the coherence of turbulence.

The paper is organized as follows: section 2 outlines the COTUR campaign and the measurement strategy; section 3 provides an overview of the data availability and describes how he lateral coherence is studied using parallel scanning beams. Finally, section 4 illustrates the potential of the data set for future research.

2 The COTUR campaign

2.1 Site description

The COTUR campaign took place between February 2019 and April 2020 in a coastal area, at Obrestad lighthouse, in southwestern Norway. Several sites on the Norwegian coast were considered for the measurement campaign. The most important criteria were (i) the local wind conditions, preferably westerly winds with large fetch over the ocean, (ii) the absence of mountains close to the coast, which may disturb the flow at a mesoscale level, (iii) ease of access to the measurement site and (iv) availability of electricity and broadband internet.

Obrestad Lighthouse, located $50\,\mathrm{km}$ south of the city of Stavanger (fig. 1), was found to be the most suitable site for this campaign. The topography behind the lighthouse is relatively flat up to $10\,\mathrm{km}$ inland. The site was chosen for its good exposure to strong seaward winds combined with easy access from the road. This ensured that the installed DWLs and the radiometer could be continuously operated, remotely monitored and physically accessed for maintenance during the campaign.

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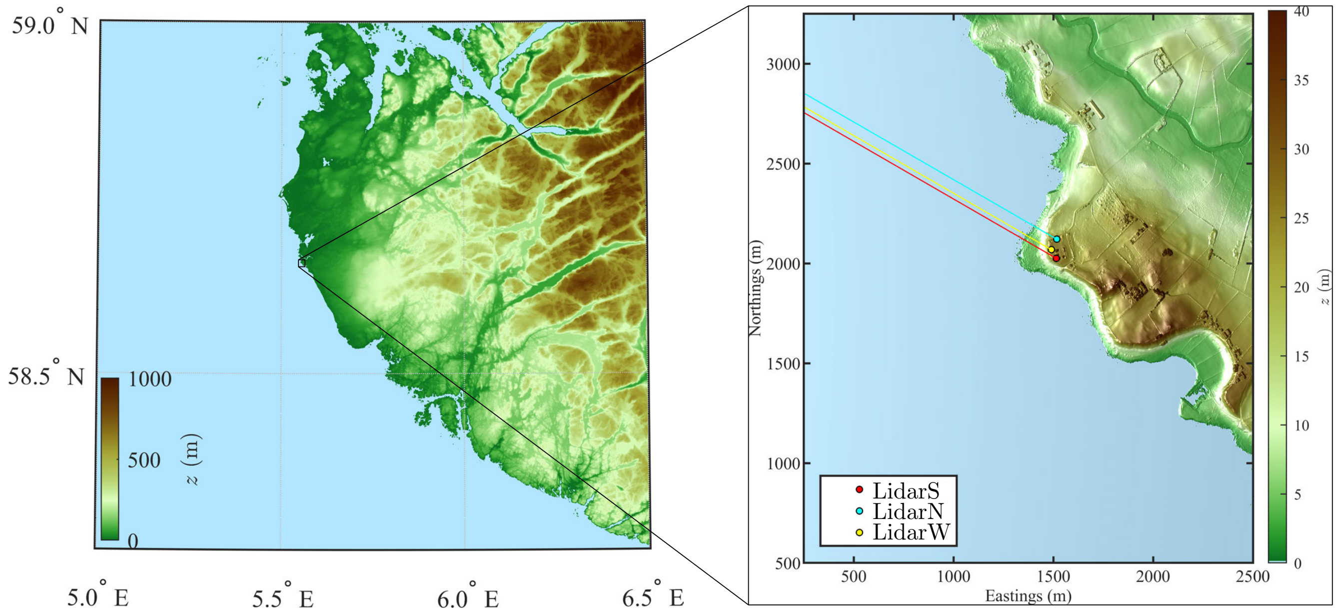

Figure 1. Location of the Obrestad lighthouse on the south west coast of Norway with a sketch of the three Doppler wind lidars named LidarS, LidarN and LidarW pointing toward a direction of 300°.

The lighthouse is situated on a small plateau $25\,\mathrm{m}$ asl, to the east of an escarpment with steep slopes between 25° and 35° (fig. 2), which can modify the static and dynamic flow characteristics at a microscale level. This escarpment is twice as high as the Bolund hill, which was extensively studied to improve the modelling of atmospheric flow in complex terrains (e.g. Berg et al., 2011; Bechmann et al., 2011; Lange et al., 2016; Ma and Liu, 2017). Results from the Bolund hill experiments suggest that the escarpment might affect the flow characteristics up to $50\,\mathrm{m}$ above the instruments. Above the sea, the wind field may also be disturbed by the coastline up to several hundreds of meters from the shore (Emeis et al., 1995).

Long-term records from a weather station located at Obrestad Lighthouse and operated by the Norwegian Meteorological Institute indicate that the wind blows generally either from north-west or south-east, i.e. parallel to the coast (fig. 3). Considering the period from March 2019 to March 2020, a similar wind rose is observed as for the period spanning from 1990 to 2020. However, wind records with a direction from 180° to 270° were slightly more common than usual. Such directions were desirable to remotely study offshore wind conditions from the instruments located onshore.

2.2 Instrumentation

2.2.1 Doppler wind profiler Leosphere WindCube v1

The vertical profiles of the mean wind speed and mean wind direction at the Obrestad lighthouse were recorded by a Leosphere WindCube v1 profiling Lidar (fig. 4). The WindCube v1 measurement principle is based on a Doppler beam swinging (DBS) scanning pattern: the Lidar emits a series of near-infrared light pulses ($\lambda \approx 1.54\,\mu\mathrm{m}$) along four directions, where the azimuth of

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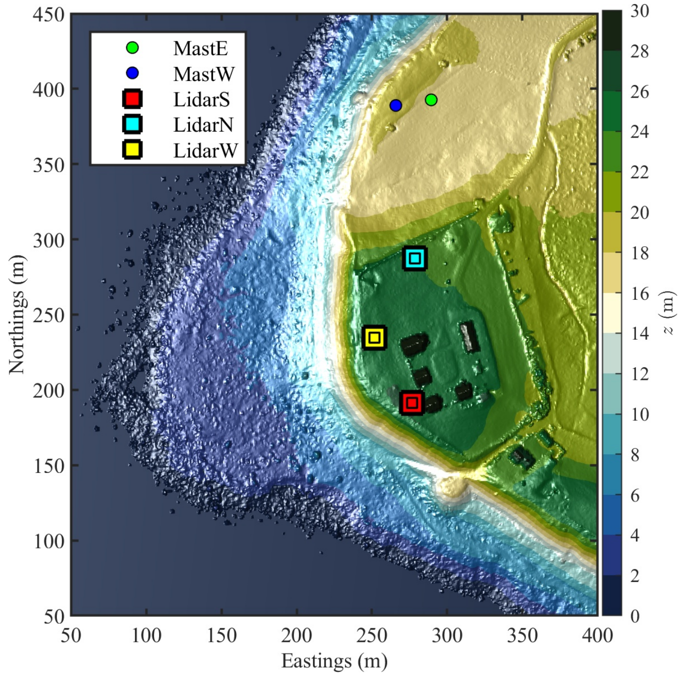

Figure 2. Local topography at the measurement site, obtained from a digital surface model generated using airborne laser instruments with a horizontal resolution of 1 m.

each beam is shifted by 90°. All four beams have a fixed elevation angle of 62°. The term "elevation angle" refers herein to the angle located in the vertical plane, between the line-of-sight and the horizontal plane. The "azimuth" refers to the angle located in the horizontal plane, measured from north in a clockwise direction. Along the line-of-sight (LOS) of the individual beams, the lidar obtains the radial velocity component from a Doppler shift of the beam, triggered by the interactions of the beam with aerosol particles that are moving with the wind. One DBS scan provides four radial wind speed values at each measurement height, which is solvable in terms of the three-dimensional wind vector (Werner, 2005).

2.2.2 Scanning Doppler wind lidar Leosphere WindCube 100S

The three scanning lidar instruments are of the type WindCube 100S from Leosphere (www.leosphere.com). They were deployed in a triangular setup where the northern instrument is named LidarN, the southern one is LidarS and the western one is LidarW (figs. 2 and 4). These instruments are pulsed Doppler wind lidars equipped with a scanner head that can orient the laser beam with an azimuth from 0° to 360° and an elevation angle from −10° to 190°. The scanning instruments were installed on top of measurement platforms constructed of Bosh Rexroth aluminium strut profiles (fig. 4). Both LidarW and LidarS were installed 2 m above ground, whereas the LidarN was installed 3 m above ground to account for the slightly lower terrain at this instrument position (fig. 2). Therefore, the scanner heads of all three instruments were located approximately 28 m asl. Finally, the location of the lidar instruments was measured by Global Navigation Satellite System (GNSS) and theodolite sightings.

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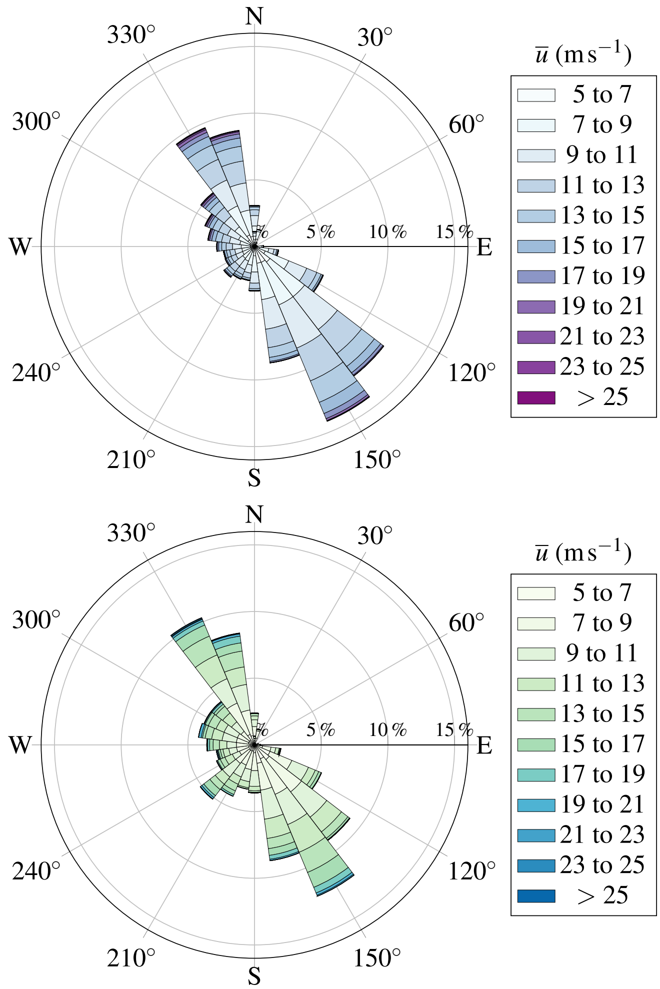

Figure 3. Wind roses computed using 10-min mean wind records from 1990 to 2020 (top) and from March 2019 to March 2020 (bottom), ten meter above the ground by the Obrestad lighthouse weather station. Only samples associated with $\overline{u} \geq 5\,\mathrm{m\,s^{-1}}$ are considered for the sake of clarity.

The study of two-point turbulence characteristics from three individual scanning lidar measurements requires the instruments to be synchronized in time. Synchronized DWLs were developed within the WindScanner.dk research infrastructure (Mikkelsen et al., 2008), which was later ramified into the long-range and the short-range WindScanner system (Mikkelsen, 2014; Vasiljevic, 2014). For the COTUR project, the long-range WindScanner system was utilized.

The long-range WindScanner client software developed by DTU (Vasiljević et al., 2016) runs on the individual lidar computers and controls the scanner motion and the laser shots according to scenarios that are received from a master control software that can run on a remote PC. The master control software can send synchronized scenarios to multiple systems and monitors the

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Figure 4. The main instrumental site of the COTUR campaign with one of the scanning lidars, Leosphere WindCube 100S (LidarN) in the center, the Leosphere WindCube v1 wind profiler to the right and the Radiometer Physics HATPRO RG4 passive microwave temperature and humidity profiler to the left. The picture is taken towards north-northwest.

synchronicity of all systems connected. The collected data are stored on both the client and the master PC. The master and client software communicate through the RSComPro protocol (Vasiljevic and Trujillo, 2014).

For advanced programming of scanning scenarios and monitoring of the measurements on a virtual globe, especially for multi-Doppler measurements, the Institute of Atmospheric Physics of the German Aerospace Center (DLR) developed an alternative master control software (LidarPlanner) featuring the RSComPro protocol. An important feature of the LidarPlanner is that it allows reading a wind direction from an external file and, upon retrieval of a new value, automatically generates modified scanning scenarios based on this information. The modified scenarios are then uploaded to the lidars and measurements are restarted. Wildmann et al. (2018) used this feature to calculate the lidar parameters for intersecting beams and triple-Doppler measurements in the wake of a wind turbine depending on the wind direction. In COTUR, the azimuth of the lidar scenarios was simply adjusted to point all three systems into the mean wind direction, obtained from $10\,\mathrm{min}$ records by the WindCube v1.

2.2.3 Passive microwave temperature and humidity profiler Radiometer Physics HATPRO RG4

To investigate the structure of the atmospheric boundary layer at the measurement site, a Radiometer Physics GmbH (RPG) Humidity and Temperature Profiler generation 4 (HATPRO-G4) passive microwave radiometer (Rose and Czekala, 2014) was installed next to Lidar WLS100-37. The HATPRO-G4 measurements rely on detecting the radiation emitted by the atmosphere at selected frequencies of the microwave spectrum.

The HATPRO-G4 measures simultaneously brightness temperatures at 14 frequencies divided into two bands ranging from $22.24\,\mathrm{GHz}$ to $31.40\,\mathrm{GHz}$ (K-band) and $51.26\,\mathrm{GHz}$ to $58.00\,\mathrm{GHz}$ (V-band) for sensing humidity and temperature profiles, respectively (Rose et al., 2005; Rose and Czekala, 2014).

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Atmosphere's microwave (MW) emission is received at the radiometer's antenna along the instrument field of view. As the radiometer senses MW radiations that contain indirect information about the columnar distribution of temperature and humidity, profiles are retrieved based on the spectral information and observed elevation angles. Temperature is retrieved up to $10\,\mathrm{km}$, as is the humidity profile. Temperature boundary-layer scans were performed every five minutes and contribute to a higher temperature profile resolution in the lower $2000\,\mathrm{m}$.

The HATPRO-G4 proprietary software provides three retrieval methods i.e. linear-, quadratic-regression and neural networks. For COTUR, retrievals were based on neural networks by RPG's firmware training data of temperature, humidity and pressure recorded from radiosondes launched at Værnes, Sola and Ekofisk stations. The radiometer has a vertical measurement resolution of $25\,\mathrm{m}$ to $30\,\mathrm{m}$ below $1\,\mathrm{km}$ and a resolution of $100\,\mathrm{m}$ between $1\,\mathrm{km}$ and $10\,\mathrm{km}$ above ground. An in-house retrieval algorithm was utilized for cases where the RPG firmware retrieval database did not represent properly the atmospheric conditions (Saavedra G. and Reuder, 2019). During the COTUR campaign, the HATPRO-G4 was installed with its field of view bearing westerly towards the open sea (fig. 4 left) and was operated in Boundary-Layer sensing mode with ten elevation angles from $4.2°$ to $90°$ every five minutes.

2.2.4 Sonic anemometers on hydraulic masts

From the 16-03-2020 to 29-03-2020, two telescopic meteorological masts PT180-6-NC from Clark Masts were deployed in an open area, $20\,\mathrm{m}$ from each other, ca. $100\,\mathrm{m}$ north to LidarN (fig. 5). Each mast was instrumented with one sonic anemometer on its top(fig. 5), approximatively $11\,\mathrm{m}$ above ground. The measurement volumes of these anemometers were, therefore, located ca. $28\,\mathrm{m}$ asl. These additional measurements aimed to compare turbulence characteristics estimated by the scanning lidars with those estimated from the sonic anemometers. The anemometers are Gill WindMaster sonic anemometer operating at a sampling frequency of $20\,\mathrm{Hz}$. The scanning beams of the lidars WSL37 and WSL40 were orientated towards each mast at a fixed azimuth of $5.3°$ and a zero elevation angle, such that their beams were parallel and horizontal. The choice of azimuth resulted in beams almost intersecting with the anemometer location on each mast.

A northerly or southerly wind direction offered suitable conditions for comparison between the sonic anemometers and the lidars data as the flow was approximately parallel to the LIDAR beams. The potential effect of the terrain on the local flow conditions was more limited for northerly winds, which were found to be best suited to validate the ability of the lidars to capture the lateral coherence of turbulence.

3 Method

3.1 Measurement and scanning strategy

To study the horizontal coherence, the scanning lidars operated in a fixed line-of-sight (LOS) scanning mode, i.e. with a fixed azimuth and elevation angle. To include as many turbulence scales as possible and to reduce the statistical uncertainties associated with the coherence estimates, the scan duration for each LOS scan was set to $50\,\mathrm{min}$.

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Figure 5. Telescopic masts mounted in a field, approximately 100 m north to LidarN, separated by 20 m from each other and equipped with one 3D sonic anemometer on their top at a height of 11 m above ground level.

160 The LOS scans were performed with a pulse length of 100 ns, a window size of 64 points for the fast-Fourier transform, a pulse repetition rate of 40 kHz and an accumulation time of 1 s. This corresponds to a sampling frequency of 1 Hz and a probe volume of approximately 25 m length. The range gates were set to 25 m with a maximal scanning distance of 1975 m, resulting in 78 range gates. The azimuth, which corresponded to the last reported 10 min averaged wind direction at 75 m above the ground, i.e. approximatively 100 m asl, was provided by the WindCube v1 and updated before the start of each new LOS scan.

165 As the campaign aimed to study atmospheric turbulence for wind energy applications, the LOS scans were performed with three predefined elevation angles of 2.0°, 3.4° and 4.9°. At a distance of 1200 m from the lidar locations, these angles correspond to altitudes of 70 m, 100 m and 130 m, respectively. Considering the case of a large offshore wind turbine positioned at a distance larger than 1 km from the shore, the choice of these elevation angles permits the study of the flow over the typical extension of the rotor disk. With the chosen low elevation angles, potential contamination of the along-beam velocity component by the vertical wind component can be neglected.

Initially, the lidars were programmed to perform a repeating series of three consecutive LOS scans, where each scan used one of the three predefined elevation angles. Utilizing the WindScanner software, all three scanning lidars performed time-synchronized measurements with identical azimuth and elevation angles during each scan. For LOS scenarios, the three beams of the different scanning lidars were thus orientated parallel to each other.

175 Within the first month of the measurement campaign, it was discovered that the scanning lidars had a “homing” issue, i.e. the lidar’s scanner head azimuth reference system was no longer calibrated with respect to true north. As a result of the lost homing, the laser beam of the scanning lidar’s was no longer pointing into the geographic azimuth direction (i.e. relative to true north) provided by the WindCube V1. Therefore, a series of short plan-position-indicator (PPI) scans were additionally programmed in which the lidar’s respective laser beams were directed towards the top of the lighthouse. Since the geographic azimuth

direction of the lighthouse's upper part was known for each of the respective scanning lidar's, the PPI scans were used in the post-processing of the data to identify any period where one lidar had lost its homing. Whenever the lidars were operating with correct azimuths, the lighthouse was visible in the respective PPI-scans due to range gate blending. To minimize the potential occurrence of the homing issue, the orientation of the lidar scanner heads was visually checked during the regular maintenance intervals. Furthermore, the Delta Tau Turbo PMAC motion controller (Hutson, 2018), which governs the motion of the scanner head, was reset whenever one of the lidars reported radial wind speeds and carrier-to-noise (CNR) values thoroughly different compared the other two scanning lidars. In November 2019, the WindCube V1 stopped operating due to water ingression into the instrument. To orientate the laser beams of the scanning lidars into the prevailing wind direction at $100\,\mathrm{m}$ asl, the wind direction was derived from DBS scans performed with the scanning lidars itself.

The WindCube v1 was programmed to simultaneously measure the mean wind speed at ten vertical levels between $40\,\mathrm{m}$ and $250\,\mathrm{m}$ above the instrument. The range gates were linearly spaced every $25\,\mathrm{m}$, except at the lowest two measurement levels, where the range gates were $40\,\mathrm{m}$ and $50\,\mathrm{m}$ above the instrument. One complete DBS scan takes approximately $4.6\,\mathrm{s}$. The $10\,\mathrm{min}$ mean wind direction estimated $75\,\mathrm{m}$ above the WindCube v1, i.e. approximatively $100\,\mathrm{m}$ asl, was used to align the laser beams of the three scanning Doppler wind Lidar systems (section 2.2.2) into the mean wind direction. This height was chosen to limit the influence of the escarpment on the local flow conditions and to consider velocity records as close as possible to the hub height of a multi-megawatt offshore wind turbine.

Therefore, the sequence of scan scenarios performed during the measurement campaign was (i) $50\,\mathrm{min}$ LOS scan at one of the predefined elevation angles followed by (ii) a series of short PPI scan, totally lasting 15 minutes, before advancing to a new LOS scan with a different azimuth and elevation angle. From November 2019, a 10-minute DBS scan scenario was run after the PPI scan scenario to determine the 10-minute mean wind direction at $100\,\mathrm{m}$ asl, which served as updated azimuth input for the following LOS scan.

Due to the location of the Lighthouse and the adjacent buildings, the scanning lidars were installed in a triangular set-up, with unequal longitudinal and lateral distances between the instruments (Figure 2). Consequently, for LOS scan scenarios, the lateral separation between the lidar's laser beams was a function of the geographic azimuth and thus depended on the wind directions. As the buildings partially limited the lidar's LOS scan view towards easterly to southerly directions, the lidar laser beams were orientated into the mean wind direction for winds blowing within the free view sector $190°$ to $350°$, and orientated into the opposite mean wind direction for winds coming from all other directions when performing LOS scan's. Note that buildings prevented Lidar WLS100-37 from performing LOS scans towards south.

3.2 Lidar data processing for coherence analysis

Although the majority of the performed LOS scan scenarios have a duration of $50\,\mathrm{min}$, instrument acquisition errors led occasionally to loss of data and resulted in time series that were shorter than $30\,\mathrm{min}$. In the MABL, turbulence characteristics are typically studied using records longer than $30\,\mathrm{min}$ (Smith, 1980; Andersen and Løvseth, 2006; Cheynet et al., 2018). This aims to reduce the statistical uncertainties (Lumley and Panofsky, 1964; Kaimal and Finnigan, 1994), but also ensures the

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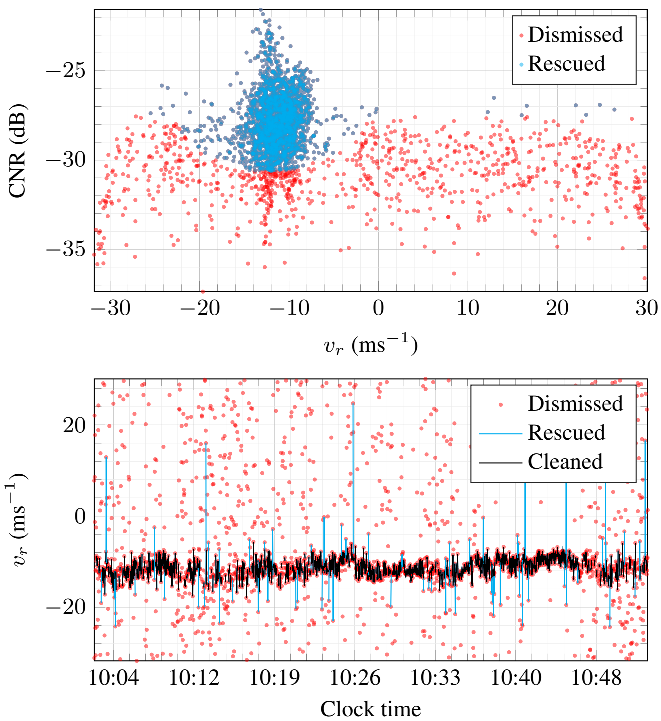

Figure 6. Top panel: scatter plot of the CNR versus the along-beam velocity on 25-10-2019 from 10:03 to 10:52 for the range gate located 275 m away from the lidars. Bottom panel: Corresponding time series showing the dismissed and rescued samples using the Mahalanobis distance and the cleaned data after application of outlier analysis based on the median absolute deviation.

passing of a sufficiently large number of eddies through the instrument measurement volume for precise estimation of the flow characteristics. Therefore, collocated LOS scan scenario time series with a duration shorter than 30 min were dismissed.

Each instantaneous LOS velocity record is associated with a CNR value, which can be used to eliminate outliers. One straightforward approach relies on a fixed value of the CNR, generally between -24 dB and -28 dB, below which data are discarded. Some recent studies (Beck and Kühn, 2017; Valldecabres et al., 2018; Alcayaga, 2020) argue that setting a fixed threshold value for the CNR can cause unnecessary exaggerated data removal, which can be a critical issue when the overall data availability is low. While Beck and Kühn (2017) and Valldecabres et al. (2018) used an iterative method based on a moving standard deviation window to increase the data availability, we used herein a two-stage method without iteration. The first stage aimed at "rescuing" realistic velocity data with a CNR below -27.5 dB. This was achieved using the Mahalanobis distance (Mahalanobis, 1936), which describes how many standard deviations away a point is from the mean value of a distribution. Any point located at a Mahalanobis distance beyond 20 was considered as an outlier and dismissed. In addition, any measurements with a CNR below -35 dB was automatically removed (fig. 6).

As shown in fig. 6, not all the outliers are eliminated after the first stage. The second stage relies on an outlier detection algorithm relying on the absolute deviation around the median (Leys et al., 2013). A moving median filter with a window

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length of $200\,\mathrm{s}$ was applied to the time series. The resulting local median values were then used to compute the median absolute deviation (MAD) (Hampel, 1974; Leys et al., 2013). Any point that was more than three MAD away from the median was classified as an outlier.

The analysis of second-order turbulence characteristics requires stationary records. The first and second-order stationary assumptions were, therefore, assessed using the moving mean and moving standard deviation with a window length of $10\,\mathrm{min}$. Samples with a maximal relative difference below $20\,\%$ between the static mean and moving mean and below $50\,\%$ between the static standard deviation and moving standard deviation were assumed to be stationary. The threshold value is larger for the second-order stationary test, because second-order statistics have larger statistical uncertainties than first-order statistics for the same averaging time. The relatively large threshold value of $50\,\%$ is chosen as the coherence is less sensitive to non-stationary fluctuations than one-point turbulence characteristics (Chen et al., 2007). Using this approach, approximately $35\,\%$ of the time series available for analysis were detected as non-stationary.

3.3 Coherence modelling

The spatial correlation of the velocity records is assessed at different wavenumbers (or frequencies) using the coherence function. In the following, the horizontal coherence of the along-wind component u between two points located in a horizontal plane, at coordinates (x_1, y_1) and (x_2, y_2) is defined as

$$\mathrm{coh}_u(x_1, y_1, x_2, y_2, f) = \frac{S_u(x_1, y_1, x_2, y_2, f)}{\sqrt{S_u(x_1, y_1, f) S_u(x_2, y_2, f)}} \tag{1}$$

where $S_u(x_1, y_1, x_2, y_2, f)$ is the two-point cross-spectral density of the u component; $S_u(x_1, y_1, f)$ and $S_u(x_2, y_2, f)$ are the one-point spectrum of the u component measured at the locations (x_1, y_1) and (x_2, y_2), respectively. In eq. (1), coh_u is a complex function. Its real part γ_u is named co-coherence and its imaginary part ρ_u is the quad-coherence. Whereas the co-coherence reflects the simultaneous fluctuations of velocity in the crosswind direction, the quad-coherence reflects the presence of shear.

For a given frequency, the quad-coherence can be represented as an anti-symmetric matrix because $\rho_u(x_1, y_1, x_2, y_2, f) = -\rho_u(x_2, y_2, x_1, y_1, f)$. On the other hand, the co-coherence can be modelled as a symmetric matrix. The co-coherence contributes to the computed turbulent load through the so-called joint-acceptance function (Davenport, 1962). For the simplified case of a horizontal line-like structure perpendicular to the mean flow direction and the k^{th} mode of vibration, the joint-acceptance function is

$$J_k^2 = \frac{1}{\mathrm{A}} \int_0^H \int_0^H \phi_k(y_1) \mathrm{coh_u}(y_1, y_2, f) \phi_k(y_2)\, \mathrm{d}y_1\, \mathrm{d}y_2 \tag{2}$$

$$\mathrm{A} = \int_0^H \int_0^H |\phi_k(y_1)\phi_k(y_2)|\, \mathrm{d}y_1\, \mathrm{d}y_2 \tag{3}$$

where ϕ_k is the k^{th} mode-shape of the structure and H its height. From eq. (2) it follows that the double integration of the quad-coherence over y_1 and y_2 is zero because it is an anti-symmetric matrix. Therefore, only the co-coherence γ_u is studied in the following.

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The terms lateral and longitudinal co-coherence refers herein to the co-coherence calculated in a horizontal plane in the crosswind and along-wind direction, respectively. In the following, the assumption of homogeneous turbulence implies that the co-coherence is expressed as a function of the spatial separations d_x and d_y instead of the spatial coordinates. The most straightforward approach to estimate the lateral co-coherence of natural wind is to use at least two anemometers, at the same measurement height, located along a line perpendicular to the wind direction, as done by e.g. Shiotani (1969); Pielke and Panofsky (1970); Ropelewski et al. (1973).

The co-coherence of natural wind can be empirically described using an exponential decay (Davenport, 1961; Pielke and Panofsky, 1970). For lateral separations, it is expressed as

$$\gamma_u(d_y, f) \approx \exp\left(\frac{-C_y d_y f}{\overline{u}}\right) \tag{4}$$

where d_y is the lateral distance between two measurement locations; C_y is ab empirically-determined decay coefficient; f is the frequency in Hz and $\overline{u}$ is the mean wind speed averaged between each pair of sensors.

The Davenport model is widely used for its simplicity. For wind turbine design, it is the fundamental model upon which more advanced models are built and applied to e.g. synthetic turbulence generation (Jonkman, 2009). In wind engineering, the study of the coherence is motivated by the need to assess the Davenport decay coefficient C_y and C_z for lateral and vertical separations, respectively. When measured on-site, these coefficients may substantially differ from the value provided in standards and codes. Improved decay coefficient estimates can lead to reduced construction costs or more robust design, adapted to environmental conditions harsher than predicted.

It is unclear whether C_y can be derived from the knowledge of C_z. Both decay coefficients depend likely on the atmospheric stability and the terrain roughness (Ropelewski et al., 1973; Soucy et al., 1982; Cheynet et al., 2018). Schlez and Infield (1998) suggested that for a given turbulence intensity, the decay coefficient of the lateral co-coherence is independent of the mean wind speed. In the surface layer, the dependency of the decay coefficients on the spatial separation and measurement height has been highlighted for both lateral and vertical separations (Kanda and Royles, 1978; Perry et al., 1978; Shiotani et al., 1978; Kristensen et al., 1981; Cheynet et al., 2017b; Bowen et al., 1983; Cheynet, 2018), reflecting the increase of the size of the eddies further from the ground.

In the case of anemometers mounted on masts, the wind direction is not always normal to the linear sensor array. In this situation, the yaw angle, defined as the angle between the wind direction and the normal to the sensor array is different from zero. As the distance d between two anemometers becomes larger than the corresponding crosswind distance d_y (fig. 7), the longitudinal distance d_x becomes non-zero. Consequently, a time delay between pairs of velocity record is introduced. Although the phase delay was studied in the 1970s in boundary layer meteorology (Pielke and Panofsky, 1970; Ropelewski et al., 1973), it is rarely modelled for wind loading on structures.

To estimate the lateral co-coherence with a non-zero yaw angle, the crosswind distance d_y is used instead of the distance d between the sonic anemometers (e.g. Saranyasoontorn et al., 2004). In addition, the time delay should either be corrected or modelled. The correction can be done assuming turbulence to be frozen (Taylor, 1938), such that the time delay is approximated by $d_x/\overline{u}$. To model the time lag, it is possible to use the shift property of the Fourier transform, which lead to the introduction of

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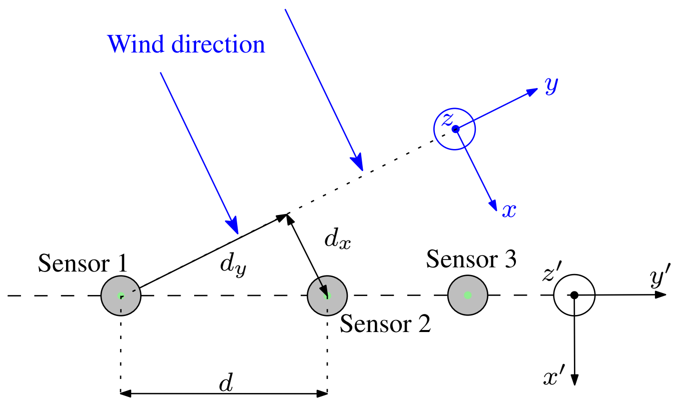

Figure 7. Sketch of a typical configuration of three anemometers (sensors 1, 2 and 3) mounted at the same height along a linear array of masts to study the lateral co-coherence of wind. This sketch is used for illustrative purpose only and does not reflect the instrumentation of the COTUR campaign.

a cosine term in the Davenport model

$$\gamma_u(d_x, d_y, f) \approx \exp\left(\frac{-C_y d_y f}{\overline{u}}\right) \cos\left[\frac{2\pi d_x f}{\overline{u}}\right] \tag{5}$$

where d_x and d_y denote the longitudinal and lateral separations, respectively. A short comparison between the co-coherence with a modelled or corrected time lag is available in Cheynet et al. (2017b, Fig. 11).

An additional decay coefficient $C_x \neq 0$, representing the loss of correlation of eddies in the along-wind direction can be introduced to account for the fact that Taylor's hypothesis of frozen turbulence is not valid at every frequency. Studying the value of C_x provides additional information on the structure of turbulence. A refined model to study the co-coherence in the horizontal plane is, therefore,

$$\gamma_u(d_x, d_y, f) \approx \exp\left\{-\frac{f}{\overline{u}} D\right\} \cos\left[\frac{2\pi d_x f}{\overline{u}}\right] \tag{6}$$

$$D = \sqrt{(C_x d_x)^2 + (C_y d_y)^2} \tag{7}$$

To account for the limited size of the gusts compared to the spatial separations (Irwin, 1979; Kristensen and Jensen, 1979), additional decay coefficients could be introduced, but these were found small enough to be neglected in the present study.

Due to the triangular set-up of the scanning lidars in COTUR, the measurement volumes were not co-located in the crosswind direction even though the laser beams were directed into the mean wind direction. Denoting the centre of two volumes in a horizontal plane as A_1 and A_2 (fig. 8), their along-wind and crosswind separations are d_x and d_y. This situation can be related to the case of an array of sonic anemometers recording a flow with a yawed wind direction (fig. 7). Using the aforementioned lidar setup (section 2.2), the co-coherence can, therefore, be studied using eq. (6), provided that the distances d_x and d_y between each range gate are known. As the scanning beams were parallel and aligned with the mean wind direction, the estimation of d_x and d_y is rather simple.

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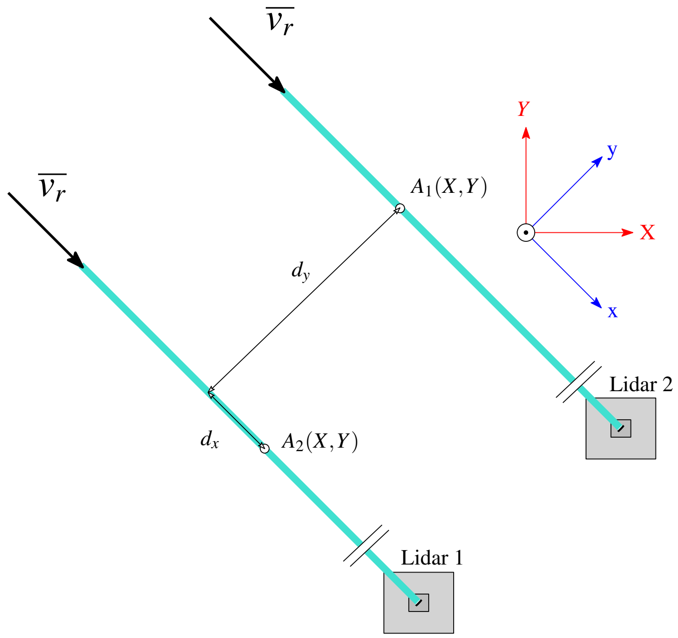

Figure 8. Schematic of the distances d_x and d_y defined by the two closest range gates for a given scanning distance.

Equation (6) is a two-parameter function where C_x and C_y need both to be determined from measurements. Using synchronized pulsed DWL instruments, the coefficients C_x and C_y can be either simultaneously or independently estimated using a least-square fit of eq. (6) to the full-scale co-coherence estimate. The simultaneous identification of C_x and C_y is straightforward but the final value of C_x can be sensitive to the initial guess. The separate estimation of C_x and C_y is more cumbersome but also more robust. This second approach is possible using pulsed DWLs which provide simultaneous measurements along the scanning beams, for which the coefficient C_x can be estimated using a single lidar instrument (Cheynet et al., 2017b). Once C_x is identified, the second coefficient C_y can be obtained by least-square fitting eq. (6) to the horizontal co-coherence. In section 4, the simultaneous fitting of the decay coefficients is adopted for the sake of simplicity.

Although the scanning beams were pointed slightly upwards during the COTUR campaign to study the flow below and above the hub height of a typical large offshore wind turbine, the elevation angles were small, such that the vertical separations between adjacent measurement volumes were negligible. This assumption implies, nonetheless, that for a selected range gate from a reference lidar instrument, the two closest measurement volumes should be selected. Finally, the requirement of stationary fluctuations was fundamental to ensure that the scanning beams were parallel to the mean wind direction as the azimuth was updated once every hour only.

The co-coherence is generally estimated with large uncertainties if a single time series is used. These uncertainties can be reduced if low spatial separations are considered, i.e. crosswind distances below 20 m to 25 m or by increasing the record duration. Another alternative is to increase the spatial resolution by measuring the flow in more than two positions, as in Cheynet et al. (2016a) where the lateral co-coherence was estimated using 26 locations. The statistical uncertainties can also be

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reduced using an appropriate power spectral density (PSD) estimate. In the present study, the co-coherence was computed using Welch's algorithm (Welch, 1967) with multiple segments and 50 % overlapping. To assess the sensitivity of the co-coherence estimates on the number of segments and, therefore, on their duration, the co-coherence was computed with segments of 90 s to 600 s. Negligible differences were found between the different segment lengths and a value of 180 s was finally chosen as a compromise between frequency resolution and smoothness of the co-coherence estimates.

The probe volume averaging modifies the estimation of the co-coherence since the scanning beams cannot be perfectly aligned with the instantaneous wind direction. Nevertheless, the resulting spatial averaging effect may have a limited influence on the co-coherence estimation, since the latter relies on a normalization of the two-point cross PSD by the one-point PSD densities (Cheynet et al., 2016a). Debnath et al. (2020) recently found that the spatial averaging may lead to an over-prediction of the magnitude coherence in the low-frequency range if the probe volume is substantially larger than a typical length scale of turbulence. Further studies are, therefore, required to clarify the influence of the probe volume averaging on the estimation of the coherence.

In brief, the fitting procedure is highly sensitive to several parameters: (1) the accuracy of the alignment between the lidar beams; (2) the consistency between the measured mean wind direction onshore and offshore; (3) the spatial averaging effect introduced by the probe volume; (4) the sampling frequency; (5) the spatial separation; (6) the range of frequencies considered for fitting; (7) the noise-to-signal ratio of the velocity data, which increases with the scanning distances; (8) the synchronization of the time series by a common clock time; (9) the number of sensors simultaneously considered (two or three lidars); (10) the local atmospheric stability and (11) the measurement height.

3.4 Assessment of the atmospheric stability

Turbulence characteristics in the MABL are also sensitive to the thermal stratification of the atmosphere (e.g Kaimal et al., 1972; Ropelewski et al., 1973; Cheynet et al., 2018). However, assessing the atmospheric stability above the sea from sensors located onshore is challenging. In the present study, the bulk Richardson number R_{ib} was computed combining sea-surface temperature, mean wind speed measurements from the scanning wind lidars and temperature profile data collected by the HATPRO radiometer. The sea-surface temperature was estimated a couple of kilometres away from Obrestad lighthouse using the level 4 GLobal Multi-scale Ultra-high Resolution sea-surface temperature (SST) analysis with a horizontal resolution of $0.01°$ (JPL MUR MEaSUREs Project, 2015). The mean wind speed was collected by LidarW at a height of $80\,\mathrm{m}$ asl. The choice of the height is justified by the need to have measurement as far as possible from the coast while being close to the maximal height attained by the scanning beam with an elevation of $2°$, which was only $94\,\mathrm{m}$. The virtual potential temperature was also estimated at a height of $80\,\mathrm{m}$ asl using the HATPRO instrument. The surface pressure recorded by the Vaisala weather station was used to extrapolate the atmospheric pressure at $80\,\mathrm{m}$ above ground level using the barometric formula (Laplace, 1805). The non-dimensional Obukhov length is then derived from Ri_b in a similar fashion as by Businger et al. (1971):

$$\zeta = \begin{cases} R_{ib}, & \text{if } -2 \leq R_{ib} \leq 0 \\ \dfrac{R_{ib}}{1-5R_{ib}}, & 0 < Ri_b < 0.2 \end{cases} \tag{8}$$

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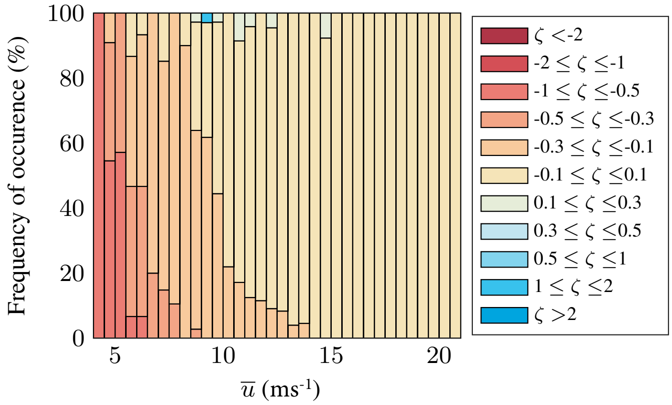

Figure 9. Histogram of the non-dimensional Obukhov length ζ using $50\,\mathrm{min}$ long records from February 2019 to march 2020, computed using the scanning lidars and the HATPRO radiometer.

The data availability of the scanning lidars was fairly low, so the distribution of stability conditions estimated this way are not representative of the stability climatology of the site. The Brunt–Väisälä frequency for wind coming from the sea will be computed without data from the scanning wind lidars in a further study using the SST data, the temperature profiles from the radiometers and the wind direction measurements from the local weather stations at Obrestad lighthouse. This will allow a better assessment of the atmospheric conditions under which the scanning lidar instruments operated poorly.

During the measurement campaign, most of the high-quality data were either associated with unstable ($\zeta < -0.1$) or near-neutral conditions ($|\zeta| < 0.1$) (fig. 9). Stable conditions ($|\zeta| < 0.1$) are more likely to occur for a wind from land, which is not dominating at the site (fig. 3). A stable thermal stratification associated with a clear sky can be associated with low aerosol concentration, during which little particle backscattering is collected by the lidars, decreasing the CNR and, therefore, the data availability (Aitken et al., 2012; Gryning et al., 2016).

4 Potential of the data sets and first results

4.1 Data availability

The data availability is examined hereafter in terms of hours and the percentage of usable data. Between the 2019-02-01 and 2020-03-29, the scanning lidars were set to operate $50\,\mathrm{min}$ per hour, i.e. a total of $8400\,\mathrm{h}$. The effective accumulated hours of data in the LOS mode was $4578\,\mathrm{h}$, $4684\,\mathrm{h}$ and $5022\,\mathrm{h}$ for the LidarS, LidarN and LidarW, respectively. This represents a data availability between $50\,\%$ and $60\,\%$ (level L0 in table 2). During the same period, the data availability of the HATPRO radiometer and WindCube V1 were $79\,\%$ and $47\,\%$, respectively.

The data availability of the scanning wind lidars is further reduced when considering only the situations where the beams of all three lidars are aligned within $\pm 20°$ with the mean wind direction (level L1 in table 2). Further post-processing depends on

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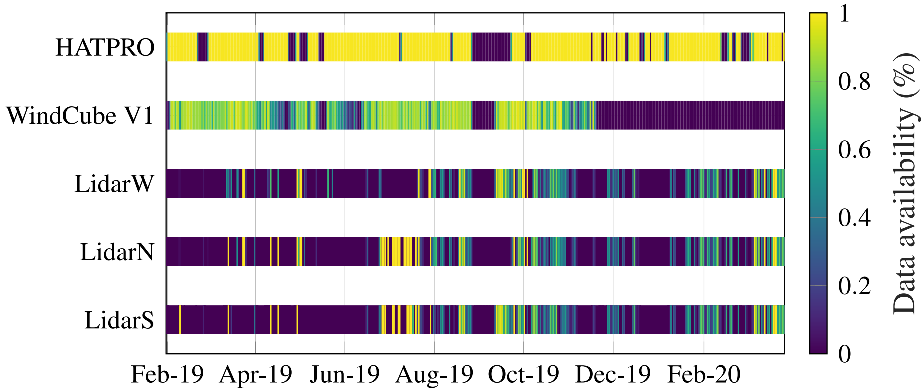

Figure 10. Daily data availability of every sensor deployed at Obrestad lighthouse from February 2019 to April 2020. Data are shown as available for LidarS, LidarN and LidarW when the scanning beams were aligned with the wind direction recorded 100 m asl.

Table 2. Scanning lidar data availability from 2019-02-01 to 2010-03-29.

Processing level	LidarS (%)	LidarN (%)	LidarW (%)
L0	54	56	60
L1	22	24	21

the flow characteristics investigated. In the following, the data processing is tailored to study the co-coherence of turbulence, which requires simultaneous measurements of two or three lidars. For other types of investigations that only require single lidar measurements, e.g. slant mean wind speed or standard deviation profiles along the slightly ascending lidar beam, the data availability is considerably higher.

4.2 Validation of the coherence estimates by sonic anemometers

The sonic anemometer records will be used in a further study to assess whether the lateral coherence of turbulence is captured properly by the long-range lidar instruments. The masts were located in hilly terrain and the sectors permitting such a validation procedure need to be identified first. Figure 11 summarizes the wind conditions recorded from 16-03-2020 to 29-03-2020 by the sonic anemometers on the top of the two hydraulic masts. During this period, the scanning beams of LidarW and LidarN were orientated toward the masts. The top panel of fig. 11 display the 10-min averaged mean wind velocity vector projected onto the scanning beam of the lidars to allow a direct comparison between the different instruments. For a southern flow, the masts are located downstream of the hill on which the lidars are installed, which is reflected by the negative angle of attack (AoA) for MastW in the bottom panel of fig. 11. However, the anemometer on MastE is located further away from the hill than the anemometer on MastW, which results in AoAs that differs by ca. 5° between the two sensors.

The middle panel of fig. 11 indicates that the positive AoAs observed on MastW are linked to a northerly flow whereas the negative AoAs are associated with a wind direction around 160°, i.e. a southeastern flow. Even if the two masts are located

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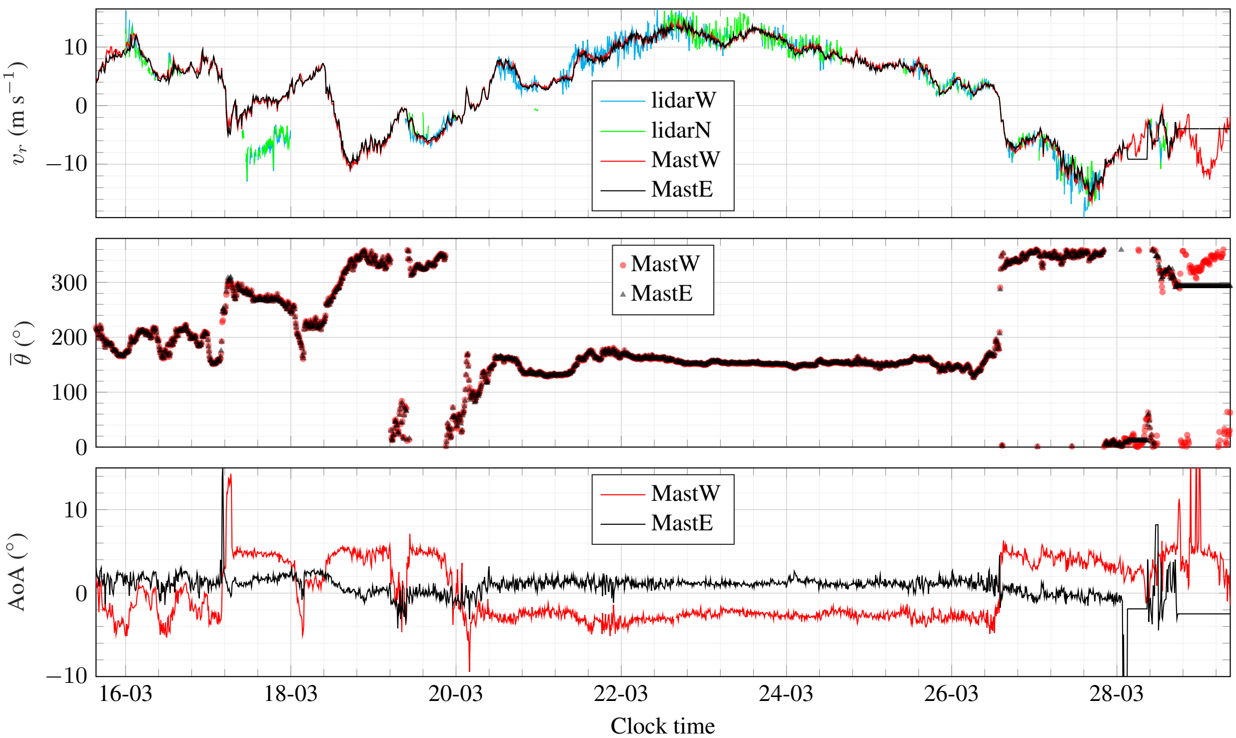

Figure 11. 10-min along-beam mean wind speed (top panel), mean wind direction $\overline{\theta}$ (middle panel) and mean angle of attack (AoA, bottom panel) recorded from 16-03-2020 to 29-03-2020 on the northern side of Obrestad lighthouse.

only twenty meters apart from each other, the flow characteristics between the two masts differ clearly due to the hilly terrain. The top panel of fig. 11 indicates that the flow might not be uniform around the masts. Flow heterogeneity within small spatial separations implies that the aerosol motion inside the probe volume of the lidar is also heterogeneous. This can result in a broadening of the Doppler spectra and, therefore, a reduced measurement accuracy (Cheynet et al., 2017a). The lidars data are noisier for the southern flow than the northern one, which may be due to the presence of flow separation downstream of the hill. Therefore, the expected comparison of the co-coherence estimates from lidar and sonic measurements will have to be conducted separately for the two main wind sectors identified.

4.3 Case study

The potential of the dataset collected is illustrated using a $50\,\mathrm{min}$ time series corresponding to a flow from southwest recorded on 25-10-2019 from 13:35 with a mean wind direction of 225°. At the height of $80\,\mathrm{m}$ asl, the non-dimensional Obukhov length was $\zeta = -0.07$, implying near-neutral conditions on the unstable side. This particular time series was chosen for two reasons: firstly, it corresponded to a mean wind direction almost perpendicular to the coastline, such that the shore had a limited influence on the flow characteristics. Secondly, it was associated with a relatively stationary record, a mean wind speed above $13\,\mathrm{m\,s^{-1}}$ at

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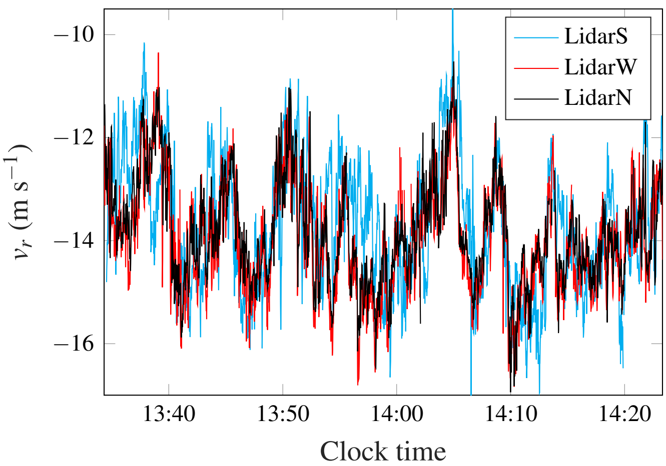

Figure 12. Along-beam velocity component recorded on 25-10-2019 by LidarN, LidarS and LidarW at $r = 1975\,\mathrm{m}$.

a height of $100\,\mathrm{m}$ asl and low measurement noise. For this record, the azimuth of the lidars was also $225°$, indicating proper communication between the WindCube v1 and the scanning instruments. The elevation angle was $4.9°$ such that for a scanning distance of $2\,\mathrm{km}$, the measurement height was almost $200\,\mathrm{m}$ asl.

The velocity fluctuations of the along-beam component, at $r = 1975\,\mathrm{m}$ from LidarN, LidarW and LidarS are shown in fig. 12. If the time series are visualized simultaneously for every range gate, a two-dimensional picture is obtained (fig. 13), which is similar to a Hovmöller diagram, except that the y-axis represents the distance from each lidar and the x-axis represents the time. Figure 12 suggests a high spatial correlation between the velocity records by LidarN and LidarW but not between LidarS and the other two scanning instruments. Although the data quality from LidarS seems good at first sight (fig. 13), its beam was likely misaligned with the other ones. The suspicion of misalignment is highlighted using the correlation coefficient between each pair of velocity records.

These correlation coefficients are computed at increasing range gates from a reference lidar, typically LidarW or LidarN. The two records selected are those located nearest from each other, which means that they do not necessarily correspond to the same range gate distance. In fig. 14, the correlation coefficient between LidarW and LidarN remains fairly high and constant with the scanning distance r, suggesting that the laser beams are fairly parallel. On the other hand, for the pair LidarW-LidarS and LidarN-LidarS, the range-dependant correlation coefficients are characterized by a sharp peak. These peaks may indicate that the beams intersect at $r \approx 450\,\mathrm{m}$ and $r \approx 550\,\mathrm{m}$, respectively, which corresponds to an offset of approximatively $7°$ for the azimuth of LidarS. The possible beam misalignment implies that there exist large uncertainties for the velocity records collected by LidarS and the study of such a dataset is outside the scope of the present work. For this reason, only the co-coherence between LidarN and LidarW is studied in the following.

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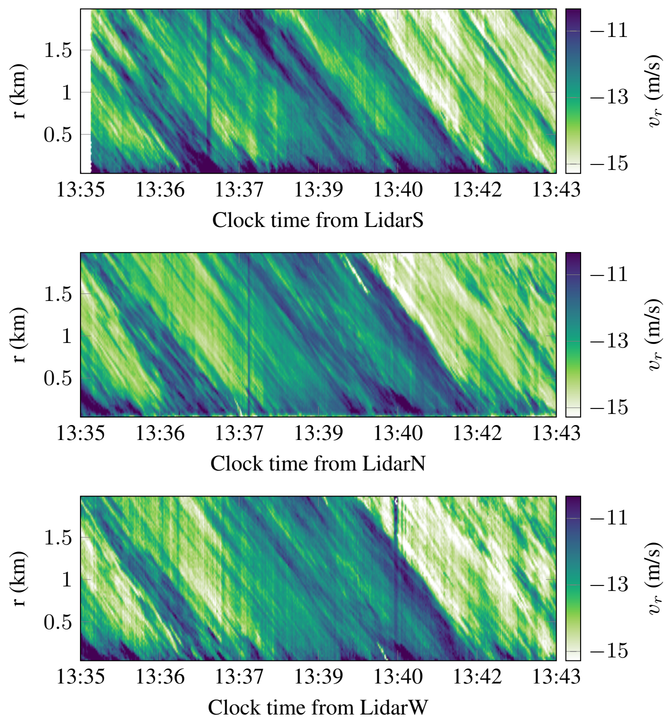

Figure 13. Along-beam velocity component simultaneously recorded on 25-10-2019 by the three scanning lidar instruments at every range gate.

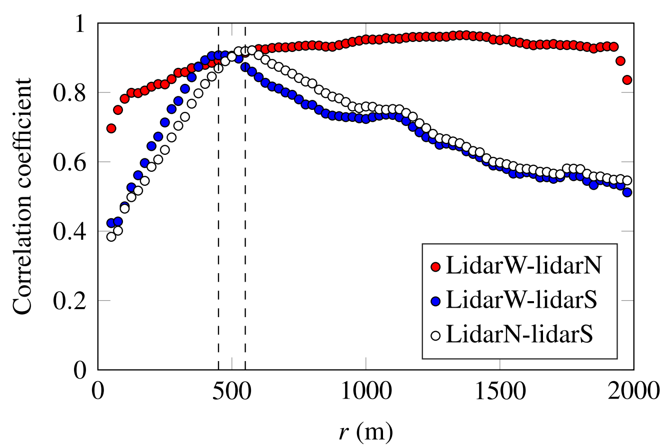

Figure 14. Pearson correlation coefficient between each pair of time series, at increasing distances from LidarW or LidarN. The dashed lines indicates the distance a which the correlation coefficient is largest for LidarW-LidarS and LidarN-LidarS.

4.3.1 Slant profiles

The slant profiles of the mean wind speed and the along-beam standard deviations were computed, taking advantage of the slightly positive elevation angles (fig. 15). For the profile of the mean wind speed, the values collected by the WindCube v1 during the LOS scans are superposed to those obtained with the scanning instruments and displayed as solid lines. The discrepancies between the mean wind speed recorded by the scanning lidars and the wind profiler are expected. These are likely due to a "coastline induction zone", which is here defined as the region upstream to the shore where the transition from sea to land induces a noticeable deceleration of the flow velocity. The profiles obtained by the scanning lidars show a strong shear at scanning distances up to $1000\,\mathrm{m}$, which correspond to heights of $113\,\mathrm{m}$ asl. The large shear suggests that the influence of the coastline on the flow characteristics could be substantial up to $1\,\mathrm{km}$ away from the coast. Another example of coastal induction zone can be found in Cheynet et al. (2017b, Fig. 17). As the measurement altitude increases with the distance to the shore, the influence of the coastline on the profiles is reduced. However, for the heights considered, the directional wind turning is not large enough to significantly affect the profiles of the mean wind speed, especially under convective conditions where wind veering is fairly small (Brown et al., 2005; Bodini et al., 2019).

The vertical profile of the standard deviation at heights above $100\,\mathrm{m}$ asl shows fluctuations that are mainly due to measurement uncertainties. For LidarW and LidarN, σ_{v_r} is almost constant between $100\,\mathrm{m}$ to $200\,\mathrm{m}$ asl, with variations below $0.04\,\mathrm{m\,s^{-1}}$. The invariability of σ_u with the height is expected under slightly convective conditions (Panofsky et al., 1977). Only LidarS shows stronger variations, in particular, an increasing turbulence level with the altitude, partly due to the misalignment between the laser beam and the mean wind direction.

The scanning lidars measured a turbulence intensity of 0.08 at $100\,\mathrm{m}$ asl, which is probably slightly lower than in reality due to the limited sampling frequency used ($1\,\mathrm{Hz}$) and the probe averaging volume. Nevertheless, this value is fairly close to the one used by e.g. the IEC standard (IEC 61400-3, 2009), documented offshore (Geernaert et al., 1987; Barthelmie et al., 1996) or near-offshore (Andersen and Løvseth, 2006). Nevertheless, some studies report also average turbulence intensities lower than in the present study, e.g. Coelingh et al. (1992) or Türk and Emeis (2010), maybe because cup anemometers were used instead of sonic anemometers.

4.3.2 Co-coherence estimates

The co-coherence is estimated as a function of the scanning distance r considering the two nearest range gates. Figure 16 shows that both C_x and C_y are range-dependant. Lower decay coefficients imply a larger co-coherence and, therefore, increased turbulent loading. The co-coherence can increase with the height (Kanda and Royles, 1978; Bowen et al., 1983; Cheynet, 2018) but also decrease with the scanning distance because the CNR becomes lower as r increases, which may be related to the presence of uncorrelated noise in the velocity records. Figure 16 shows, for example, increasing values of C_x and C_y at scanning distances beyond $1.7\,\mathrm{km}$. Any change of the environmental conditions, including local variations of the wind direction, can affect the co-coherence estimates. A further investigation of the ability of long-range lidars to describe properly the co-coherence of turbulence relies on a rigorous comparison with data from sonic anemometers on met-masts.

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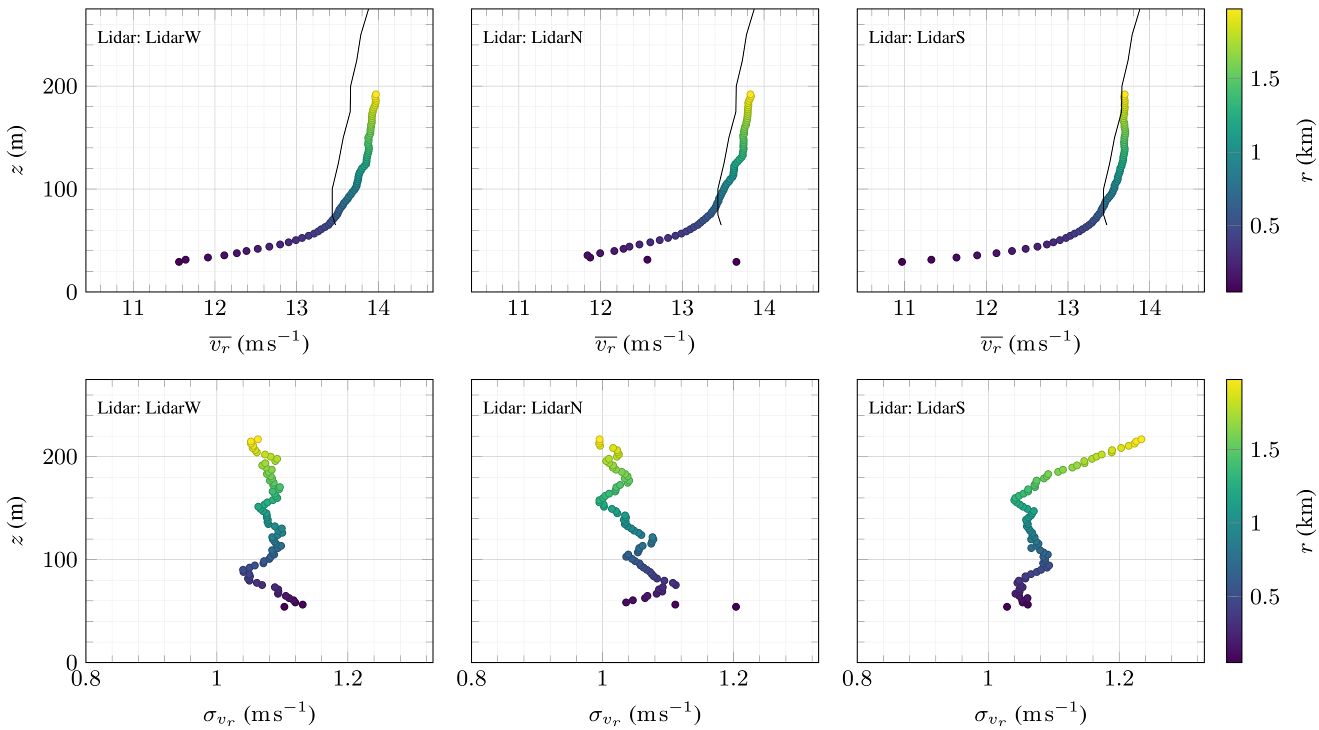

Figure 15. Top panels: Mean wind speed recorded along the beams of the the scanning lidar units (scatter) superposed to the wind profile of the Windcube V1 (solid line). Bottom panels: standard deviation of the along-beam component at increasing distances and heights on 25-10-2019 from 13:35 to 14:25.

460 A detailed analysis of the lateral co-coherence between LidarN and LidarW is shown in fig. 17 for three different scanning distances. The solid line is obtained after least-squares fitting of eq. (6) to the data at the different range gates. The large longitudinal distance $d_x = 54\,\mathrm{m}$, displayed in the bottom panel of fig. 17, is responsible for the negative co-coherence, properly captured by eq. (6). It is almost equal to the distance between LidarN and LidarW in the southwest direction. The good agreement between the fitted and estimated co-coherence in the bottom panel of fig. 17 indicates also that the alignment of the scanning 465 beams is satisfactory as eq. (6) fits the data well.

In the present case, both C_x and C_y were simultaneously estimated. Therefore the fitted value of C_x is sensitive to the initial guess used. Further improvements can be achieved by considering first the along-beam co-coherence, for which the lateral separation is zero, such that only the coefficient C_x is unknown. Then the coefficient C_y is determined using eq. (6). A single DWL can be used to study the longitudinal co-coherence (Sjöholm et al., 2010; Davoust and von Terzi, 2016; Cheynet et al., 470 2017b; Debnath et al., 2020; Chen et al., 2020). Also, the value of the C_x as a function of the range gate can provide additional information on the influence of the coastline on the flow characteristics.

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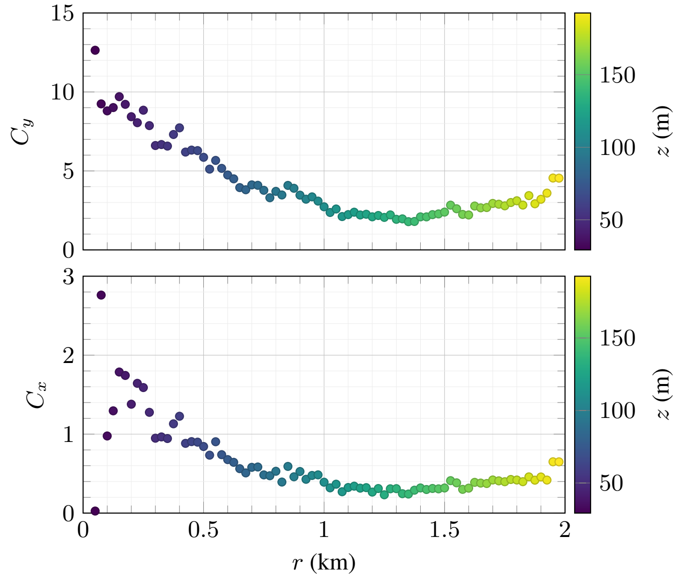

Figure 16. Decay parameters at increasing scanning distances (abscissa) and increasing heights (colorbar) obtained by fitting eq. (6) to the co-coherence between LidarW and LidarN.

4.3.3 Power spectral density of the along-beam velocity component

To model the dynamic wind load on a structure, knowledge of the PSDs of the velocity fluctuations is also essential. However, their description relies primarily on Monin-Obukhov Similarity Theory (MOST) (Monin and Obukhov, 1954), which was developed for the atmospheric surface layer and mainly validated against measurements under largely homogeneous conditions over land (e.g. Haugen et al., 1971; Kaimal et al., 1976). The straightforward applicability of MOST for the large rotor diameters in offshore conditions is thus, at least, questionable.

The PSD of the along-beam velocity component was studied at different scanning distances and altitudes ranging from $50\,\mathrm{m}$ to $200\,\mathrm{m}$ above the sea surface (fig. 18). Two PSD estimates are first obtained using the records from LidarN and LidarW and then spatially averaged. A blunt spectral model (Olesen et al., 1984) was fitted to the velocity spectra at $z = 75\,\mathrm{m}$ to highlight the frequency range affected by the probe volume averaging, visible above $0.2\,\mathrm{Hz}$.

The PSD estimate is obtained using Thomson's multitaper method with a time-bandwidth product equal to 5/2 (Thomson, 1982). The latter method was found to be more appropriate than Welch's algorithm (Welch, 1967) to estimate the PSD of a single time series. In fig. 18, the different PSD estimates at $z = 75\,\mathrm{m}$ asl and above seem to be independent of the measurement height. This is not consistent with the surface-layer theory, predicting that a clear dependency of the velocity spectra on the measurement height z should be observed at $z < 0.1 z_i$, at least in the inertial subrange. The boundary layer height, assumed identical to the inversion height z_i, was $1153\,\mathrm{m}$ according to the passive microwave radiometer. The lack of dependency of the velocity spectrum on the height may indicate that the measurements are conducted in the mixing layer. Following Kaimal (1978, Eq. 4), the spectral peak should occurs near $f z_i / \overline{u} \approx 0.65$ but in the present case, assuming that $v_r \approx \overline{u}$, it is reached at $f \approx 0.003\,\mathrm{Hz}$,

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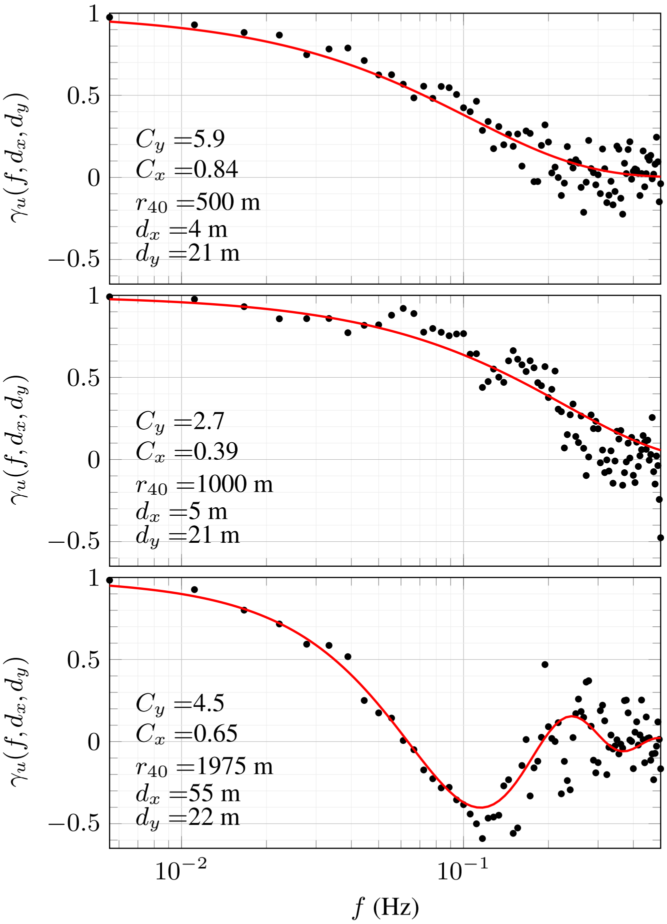

Figure 17. Estimated (scatter) and fitted (solid line) co-coherence of the along-wind component between LidarW and LidarN using range gates at 500 m, 1000 m and 1975 m from LidarW. The time series selected is displayed in fig. 12 and corresponds to an azimuth of 225° and an elevation of 4.9°.

i.e. at $f z_i/\overline{u} \approx 0.3$. The spectral gap is also visible, at frequencies below 1 mHz, which is expected for near-neutral conditions (Gjerstad et al., 1995).

It should be noted that in IEC 61400-1 (2005, Eq. 5), the velocity wind spectrum becomes independent on the height at $z > 60\,\mathrm{m}$, which is consistent with the velocity spectra displayed in fig. 18. The preliminary results highlighted in fig. 18 justify, therefore, the need to analyse more systematically the one-point velocity spectra recorded by LidarW and LidarN to assess the limit of turbulence models used in codes and standards for the design of offshore wind turbines.

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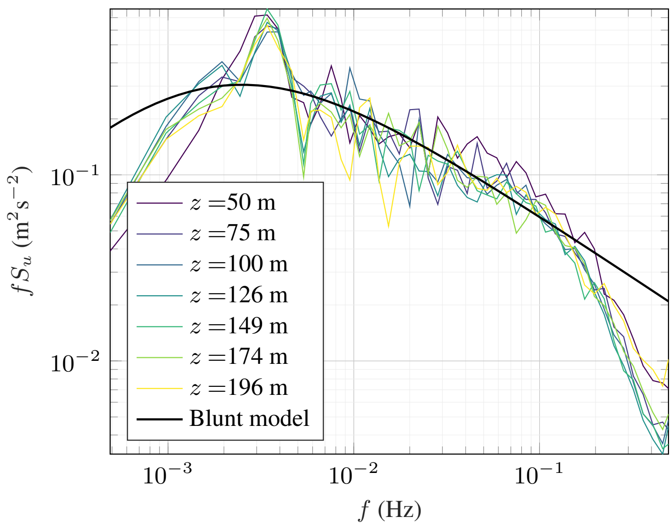

Figure 18. Power spectral density estimate of the velocity component v_r recorded on 25-10-2019 from 13:35 to 14:25 using beams parallel to the mean wind direction with an elevation angle of $4.9°$. The mean wind speed was $\overline{v_r} \approx 14\,\mathrm{m\,s^{-1}}$ at the different heights selected.

5 Conclusions

The data collected during the COTUR campaign aimed to characterize offshore wind turbulence, especially the lateral co-coherence, using remote sensing instruments located on the seaside. The novelty of the campaign lies on the combination of a passive microwave radiometer, three scanning Doppler wind lidars (DWLs) and one DWL profiler to explore flow characteristics not easily measurable using traditional anemometry. The lateral co-coherence was studied using synchronized lidars in a fixed Line-of-Sight (LOS) scanning mode with scanning beams parallel to the mean wind direction. This approach might be used to complement data collected by linear arrays of masts instrumented with sonic anemometers.

The lateral co-coherence of natural wind is significantly different from zero at low frequencies only. Therefore, it is a flow characteristic that may be investigated successfully using synchronized pulsed Doppler in a similar setup as for the COTUR campaign, i.e. parallel scanning beams oriented into the mean wind direction, a probe volume of $25\,\mathrm{m}$ and a sampling frequency of $1\,\mathrm{Hz}$. For the case at hand, the influence of the coastline on the turbulent flow characteristics may be substantial up to at least $1\,\mathrm{km}$ away from the shore. This influence was visible in the profiles of the mean wind speed and standard deviation of the along-beam velocity component, but also in the different lateral co-coherence estimates.

The combination of the lidar Planner software with the WindScanner for turbulence characterization is another novel aspect of the study. A major step towards better availability from complex lidar scanning scenarios will be to improve the robustness of the research software tools or an integration of the features into the commercial lidar software.

The data set collected during the COTUR campaign offers the possibility to cover several topics of interest for both boundary-layer micro-meteorology, wind energy, remote sensing and wind engineering:

1. The comparison of the lateral co-coherence estimated by sonic anemometers and the Wind lidars offers a unique occasion to validate the potential of long-range lidar instruments to characterize the co-coherence of natural wind.
2. The decay coefficients used to model the co-coherence displayed a dependency on the scanning distance, which needs to be investigated in more details. Further away from the coast and at a higher altitude, a smaller decay coefficient implies larger wind load on e.g. the mooring lines of floaters and the blades of offshore wind turbines.
3. The use of small positive elevation angles allows the investigation of turbulence characteristics at an increasing height from the surface. While the atmospheric stability can be estimated combining the sea-surface temperature and the data collected by the HATPRO radiometer, the latter provides also estimates of the atmospheric boundary layer height. Therefore, the limits of surface-layer scaling in the MABL can be assessed.

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Author contributions. EC, MF, JR, JBJ, YH, PSG conceived the instrumental setup. MF, BS, PSG, CD, EC, ND and JB participated in the installation of the instruments and/or their decommissioning. EC, BS, ND, JBJ, CO, MF, YH and JB were responsible for the physical maintenance of the instruments, which were remotely monitored by MF, YH, BS and PSG. CO and JB installed the meteorological masts. The lidar and radiometer data production and storage was done by MF, YH, PSG and BS. The anemometer data were stored by CO. The implementation and maintenance of the software were done by YH, MF, PSG and NW. EC extracted, processed and analysed the data. EC wrote the draft with contributions from MF and JR. All authors participated in the review of the paper.

Competing interests. The authors declare that they have no conflict of interest.

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