

Can dual pulsed scanning Doppler wind lidars measure turbulence coherence?

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Abstract. This study presents one of the first validations of horizontal turbulence co-coherence estimated using dual synchronised long-range pulsed Doppler wind lidars, with sonic anemometers as reference. The experiment was conducted in March 2020, where two WindCube 100S lidars operated in fixed line-of-sight mode with parallel beams directed towards two 3D sonic anemometers mounted on 10 m-high masts separated by ~~20-24~~ m. One-point turbulence statistics show good agreement, with $R^2 > 0.96$ for the mean along-beam velocity and $R^2 \approx 0.87-0.93$ for its standard deviation. The co-coherence of the along-beam velocity was evaluated using 27 high-quality 50-minute time series under northerly flow conditions, complemented by 46 samples under more turbulent southerly flow. The lidar-derived co-coherence agrees closely with the sonic reference when measurement noise is low. However, measurement noise in one lidar leads to a systematic underestimation of co-coherence across all frequencies. These results show that dual-pulsed scanning Doppler wind lidars can ~~reliably measure~~ be used reliably to estimate turbulence co-coherence, provided that beam alignment is accurate and measurement noise is low. Under the present near-optimal conditions, with lidar-mast distances below ~~150-160~~ m and verified alignment, dual-lidar systems provide a practical alternative to offshore masts for studying horizontal turbulence ~~coherence~~co-coherence.

1 Introduction

The coherence of turbulence is, together with the mean wind speed and the one-point turbulence spectrum, one of the three key parameters required for the design of wind-sensitive structures such as towers and bridges [1]. It describes the spatial correlation of turbulent flow variations in three dimensions [2] and is used in wind turbine design to simulate spatially correlated turbulence velocity time histories [3]. In this context, both lateral and vertical separations are of primary importance. However, the IEC 61400-1 standard does not distinguish between them [4], even though it has been known for decades that lateral and vertical coherence differ significantly [5].

In the marine atmospheric boundary layer (MABL), vertical coherence can be studied using a single offshore mast instrumented at multiple heights [6].

In contrast, lateral coherence requires simultaneous measurements at horizontally separated locations at the same height, which typically involves multiple offshore masts. The deployment and maintenance of such infrastructure are prohibitively expensive, making lateral coherence at heights relevant for offshore wind turbine design much more difficult to document. Remote sensing techniques such as scanning Doppler wind lidars offer a promising alternative, as they can probe the flow remotely over large spatial separations without requiring offshore installations. This offshore observational gap motivated the COTUR campaign, which explored dual-lidar scanning strategies to study turbulence coherence at lateral separation as an alternative to offshore masts [7]. Since the 2010s, shore-based remote sensing of atmospheric turbulence using ~~five-multiple~~ synchronised long-range scanning Doppler wind lidars has also been used to investigate one-point and two-point spectral statistics [8, 9], further illustrating the growing interest in novel measurement techniques for turbulence in the MABL [10].

The increasing use of scanning Doppler wind lidars to investigate two-point turbulence statistics relies on the implicit assumption that these instruments can ~~reliably be used reliably to~~ estimate turbulence coherence, yet this has not been rigorously validated for long-range pulsed systems. Previous validation was limited to short-range scanning lidars [11, 12], while earlier studies with pulsed lidars lacked a dedicated setup for direct comparison with sonic anemometers [13, 14]. This study, therefore, addresses the following research question: *Can dual pulsed scanning Doppler wind lidars ~~measure-be used to estimate~~ turbulence coherence?* The objective is to provide, to the authors' knowledge, the first validation of lateral turbulence coherence estimates obtained from synchronised long-range pulsed scanning Doppler wind lidars using a dedicated experimental setup. The experiment was conducted towards the end of the COTUR campaign [7], where two synchronised long-range pulsed scanning lidars were operated in a fixed line-of-sight configuration and compared directly with two closely spaced sonic anemometers. This new setup enabled a direct assessment of lidar-derived two-point statistics against an in situ reference.

This validation has direct implications for offshore wind turbine design and cost. Because IEC 61400-1 relies on a simplified treatment of turbulence coherence [4], insufficient knowledge of lateral coherence may lead either to overdesign, which increases capital expenditure, or to underdesign, which may shorten structural lifetime and increase operation and maintenance expenditure. Both effects contribute to an increased levelized cost of energy. As offshore wind remains significantly more expensive than onshore wind, improving the representation of turbulence coherence in established design methods offers a cost-effective pathway toward more reliable and economically viable turbine designs. Better estimates of the lateral turbulence coherence are ~~therefore-~~ therefore valuable not only from a scientific perspective, but also as a means to improve existing engineering practice rather than relying solely on larger turbines, new concepts or more favourable economic conditions.

The paper is organised as follows: Section 2 describes the measurement site, the scanning lidar instruments and the deployment of the telescopic masts, and explains how the sonic anemometer data are used to reconstruct the along-beam velocity ~~observed-recorded~~ by the lidars. Section 3 compares the one-point integral and two-point turbulence statistics obtained from the lidars and the sonic anemometers, with particular attention to the impact of ~~measurement noise in the lidar data~~ lidar measurement noise on the turbulence statistics. Finally, Section 3.3 discusses the implications of the results and provides recommendations for future measurement strategies to investigate the lateral turbulence coherence above the ocean without relying on offshore masts.

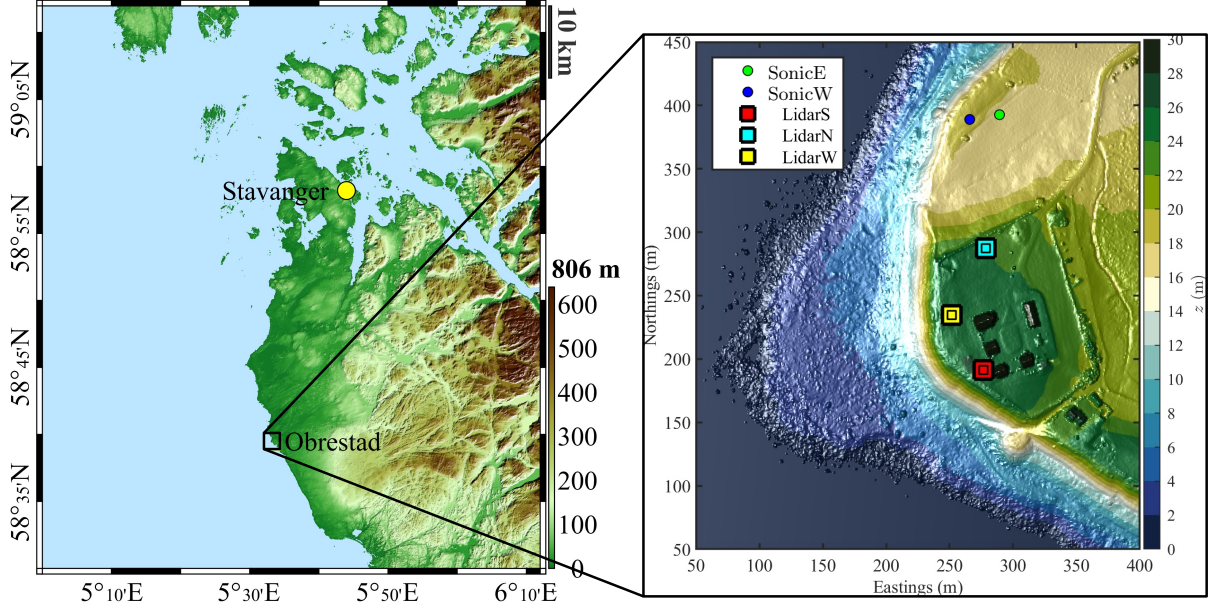


Figure 1. Topography of Southwestern Norway (left panel) with a close-up near the measurement location at Obrestad lighthouse (right panel).

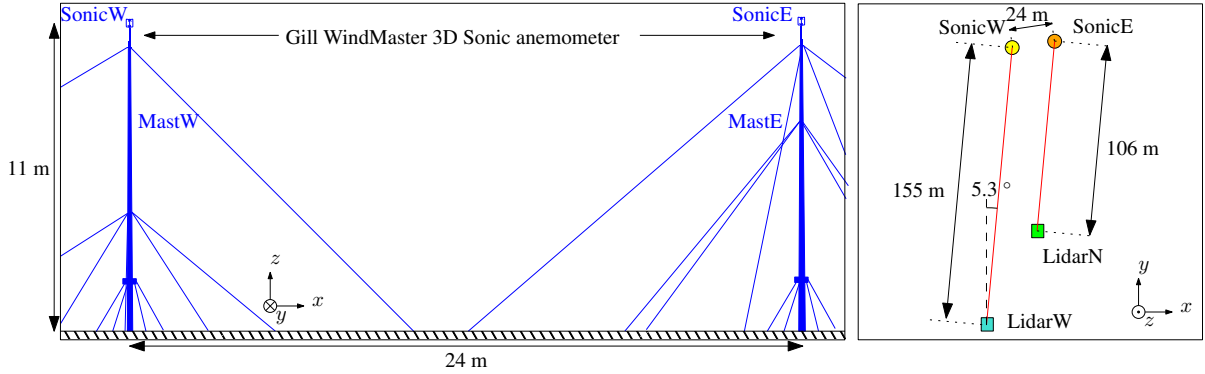


Figure 2. Sketch of the experimental arrangement used for the validation, showing a front view (left panel) and a top view (right panel). Two hydraulic masts equipped with sonic anemometers 11 m above ground were installed north of LidarN and LidarW, with a lateral spacing of 20 m 24 m. LidarN and LidarW operated in line-of-sight mode with parallel horizontal beams directed toward the masts. The distance between LidarN and SonicE is approximately 100 m.

2 Instrumentation and Methods

The COTUR campaign [7] was conducted between February 2019 and April 2020 at Obrestad lighthouse on the southwestern coast of Norway. The site is located in a flat, open coastal agricultural area. At the time of the validation campaign, the surrounding terrain had low vegetation, few isolated obstacles, and sparse buildings. Although the overall exposure was open and of low roughness, the area included numerous small-scale roughness transitions associated with changes in land cover and agricultural use (Figure 1). The instrumentation included three synchronised long-range pulsed Doppler wind lidars (WindCube 100S) deployed in a triangular configuration (LidarN, LidarW, LidarS) at approximately 28 m above sea level (asl).

During the validation phase in March 2020, presented in this study, two telescopic masts

separated by 24 m were installed about ~~100–106~~ m north of LidarN (Figure 2). Each mast was equipped with a 3D sonic anemometer at 11 m above ground (28 m asl), mounted at the top of the mast to minimise flow distortion. Following Kavaliauskas [15], a double-rotation procedure was applied to correct for sensor tilt and align the velocity components with the mean streamline. Time synchronisation between the lidar and sonic measurements was ensured using GPS time stamps and refined using cross-correlation. The ~~lidar-measurement~~ site is located at the edge of a coastal escarpment approximately 25 m above sea level, with the lidars installed a few metres above ground. For the ~~coherence-validation~~study of the coherence, northerly flow conditions (330°–360°) were primarily considered, corresponding to predominantly marine inflow with multiple upstream land–sea transitions. Additional southerly cases (120°–180°) were included to assess the performance of the lidars under more turbulent and heterogeneous conditions.

For this validation, the two WindCube 100S lidars, LidarN and LidarW, were operated with a range gate length of 25 m and a gate spacing of 2 m, resulting in strongly overlapping sampling volumes along the beam. A total of 225 range gates were used, covering distances from approximately 50 m to 500 m. The line-of-sight velocity was sampled at 1 Hz with an accumulation time of 1 s, and only measurements with a carrier-to-noise ratio greater than –27 dB were retained. The lidar beams were oriented at a fixed azimuth of 5.3° (clockwise from north) and a near-horizontal elevation angle of 0.5°. Beam alignment was verified using hard-target tests at the mast locations to ensure that the measurement volumes were as close as possible to the sonic anemometer positions. To avoid contamination from hard-target reflections, the beams were slightly offset while maintaining minimal separation between the lidar probe volume and the sonic measurement volume. For further technical details on the lidar systems, the reader is referred to [7].

To enable a direct comparison with the lidar measurements, the sonic anemometer data were projected onto the lidar line-of-sight direction. The comparison is therefore performed using the along-beam velocity component v_r for both instruments. The along-beam velocity component v_r is given by

$$v_r = -u \cos(\phi - \theta) \cos(\psi - \alpha) - v \sin(\phi - \theta) \cos(\psi - \alpha) - w \sin(\psi - \alpha), \quad (1)$$

where u , v and w are the double-rotated along-wind, across-wind and vertical velocity components, respectively, θ is the wind direction, ϕ is the lidar azimuth, ψ is the elevation angle, and α is the angle of attack. The mean along-beam velocity is denoted by $\bar{v}_r$ and its standard deviation by σ_{v_r} .

The coherence of turbulence for the along-beam velocity component, denoted hereinafter by γ_{v_r} , is a complex function whose real and imaginary parts are the co-coherence Co_{v_r} and the quad-coherence Qu_{v_r} , respectively:

$$\gamma_{v_r}(d_x, d_y, f) = \frac{S_{v_r}(d_x, d_y, f)}{\sqrt{S_{v_r,1}(f) S_{v_r,2}(f)}} \quad (2)$$

$$= Co_{v_r}(d_x, d_y, f) + i Qu_{v_r}(d_x, d_y, f), \quad (3)$$

where $S_{v_r}(d_x, d_y, f)$ is the two-point cross-spectral density of v_r , and $S_{v_r,1}(f)$ and $S_{v_r,2}(f)$ are the corresponding one-point spectra. The variables d_x and d_y denote the along-wind and crosswind separations between the two measurement locations, respectively, defined with respect to the mean wind direction. This study focuses mainly on the validation of the co-coherence, which is of primary interest for structural design.

The auto- and cross-spectral densities were estimated using Welch’s method [16] with six segments and 50% overlap. The co-coherence and quad-coherence were then obtained from the real and imaginary parts of the complex coherence, respectively. These estimates were further smoothed by bin-averaging over logarithmically spaced intervals as in Kaimal and Finnigan [17]. Ensemble-averaged estimates were computed from multiple 50-minute time series under quasi-stationary conditions.

A total of 27 high-quality 50-minute time series under northerly winds (330° – 360°) were retained for the ~~coherence~~-co-coherence validation, complemented by 46 samples under more turbulent and heterogeneous southerly flow (120° – 180°). The choice of these sectors also ensured that the beam-wise separation was predominantly crosswind, and d_x remained small. Under these conditions, the co-coherence of v_r can be interpreted primarily as a function of the lateral separation d_y . This study directly compares co-coherence estimates from lidar and sonic measurements, rather than fitting analytical ~~coherence~~-co-coherence models.

To further investigate the influence of the measurement noise on the turbulence statistics, the integral time scale T_{v_r} of the along-beam component is computed as the integral of the autocorrelation function $R_{v_r}(\tau)$

$$T_{v_r} = \int_0^\infty R_{v_r}(\tau) d\tau. \quad (4)$$

The integral time scale is a statistic with significant uncertainties in the ABL [18]. Thus, we estimate here the integral time scale by approximating the autocorrelation function with an exponential decay, following [19],

$$R_{v_r}(\tau) \approx \exp\left(-\frac{\tau}{T_{v_r}}\right), \quad (5)$$

such that T_{v_r} represents the characteristic decay timescale of the autocorrelation function. The fit is performed using a least-squares approach over the initial 30 s of the autocorrelation function, as including longer lags leads to unreliable estimates. Under this framework, the presence of uncorrelated measurement noise is expected to systematically reduce the estimated integral time scale, whereas correlated noise primarily increases the uncertainty of the estimate without introducing a systematic bias.

3 Results

In March 2020, northerly and southerly winds at Obrestad Lighthouse provided the best alignment between the mean wind direction and the lidar beams. Northerly conditions were preferred for the validation, as they are less affected by local topography. In contrast, southerly winds place the masts downstream of the hill on which the lidars are installed, leading to negative angles of attack on SonicW [15]. Figure 3 further highlights the influence of local topography on the flow. The western sector corresponds to wind from the sea, with turbulence intensities below 0.10. The northern sector exhibits turbulence intensities between 0.10 and 0.15, reflecting multiple land–sea roughness transitions. In the southern sector, turbulence intensities exceed 0.20, consistent with the masts being located in the lee of the hill, where flow separation may occur, and with additional influence from nearby obstacles such as Obrestad Lighthouse and surrounding buildings.

3.1 Integral flow characteristics

Figure 4 shows examples of synchronised along-beam velocity time series for northerly flow conditions. A good agreement is observed between SonicW and LidarW, while LidarN also

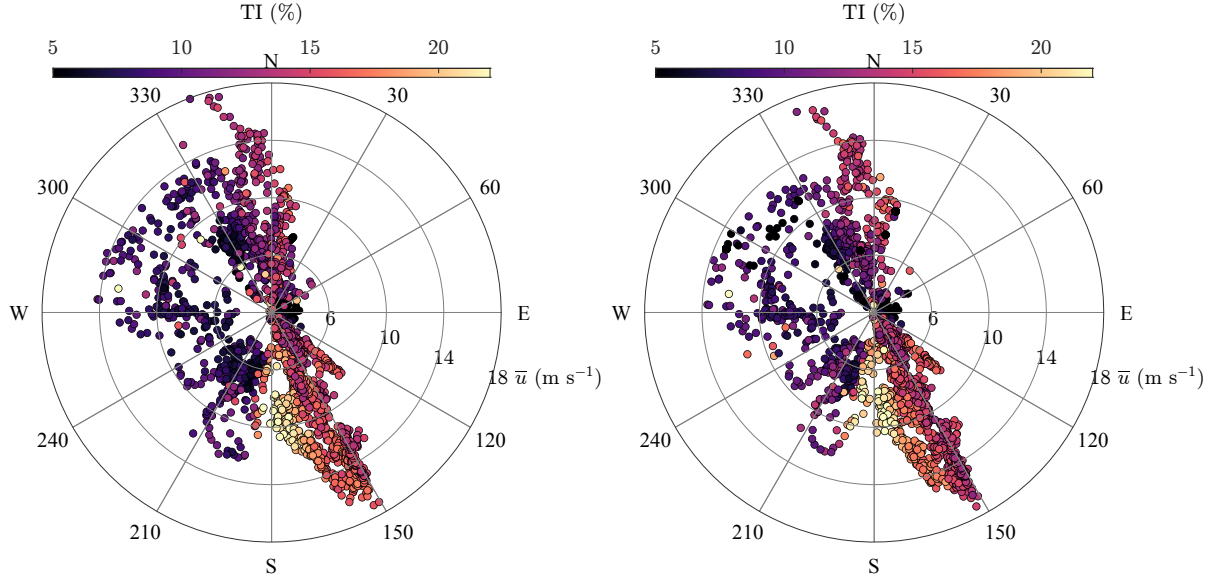


Figure 3. Mean wind speed and turbulence intensity of the along-wind component as a function of mean wind direction at 11 m above ground for SonicW (left) and SonicE (right). The statistics are based on 10-minute samples collected between 16 March 2020 and 30 March 2020 (2160 samples).

captures the main flow features measured at SonicE. However, LidarN exhibits higher high-frequency noise compared to both LidarW and the sonic measurements, consistent with the reduced agreement observed in the statistical analysis presented below. To support these qualitative observations and provide a consistent basis for coherence-coherence and quad-coherence analysis, a quantitative comparison of one-point statistics is performed. The mean, standard deviation and integral time scales of the along-beam velocity component v_r are compared to assess flow homogeneity and measurement consistency (Figure 5).

The mean along-beam velocity measured by the sonic anemometers and the lidars shows good agreement, indicating that the mean flow is approximately homogeneous at the mast locations. Coefficients of determination exceed $R^2 > 0.99$ when comparing instruments of the same type (LidarW–LidarN and SonicE–SonicW), confirming internal consistency. Slightly lower values, in the range $0.96 < R^2 < 0.98$, are obtained when comparing lidar and sonic measurements at corresponding locations (LidarW–SonicW and LidarN–SonicE), which can be attributed to differences in measurement principles and sampling volumes.

The standard deviation σ_{v_r} , which reflects the intensity of velocity fluctuations, is systematically lower for LidarW than for SonicW. This underestimation is attributed to probe-volume averaging, whereby the lidar measures the flow over a finite volume and thus smooths out small-scale fluctuations. Despite this effect, the agreement remains strong ($R^2 \approx 0.93$), with a median relative difference of about 5%. In contrast, the agreement between LidarN and SonicE is weaker ($R^2 \approx 0.87$), reflecting a higher level of measurement noise in LidarN. This noise is more pronounced for southerly winds, likely due to terrain-induced turbulence south of the site, and results in the absence of a clear systematic bias. Comparisons between instruments of the same type yield $R^2 \approx 0.95$ for the two sonic anemometers and $R^2 \approx 0.92$ for the two lidars. These results indicate either slight spatial variations in turbulence intensity or inherent random uncertainties associated with the measurement systems.

The comparison of the integral time scales exhibits larger random errors than those of the

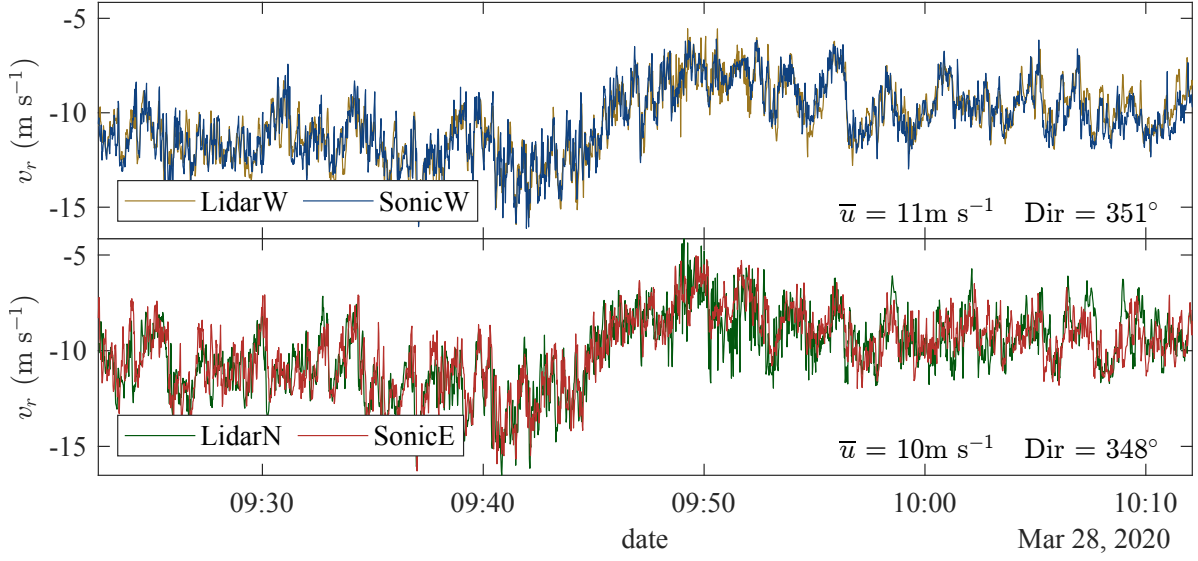


Figure 4. Synchronised along-beam velocity time series measured on 28 March 2020 for northerly flow conditions. The wind direction is approximately 350° and the wind speed is about 11 m s^{-1} at the sonic anemometer height.

standard deviation, as expected. The coefficient of determination is $R^2 = 0.88$ between the sonic anemometers on the two masts, whereas the lowest value ($R^2 \approx 0.60$) occurs between LidarN and SonicE, indicating the presence of measurement noise in LidarN. However, the absence of a systematic underestimation of the integral time scale suggests that the noise contains a correlated component. LidarW also shows some measurement noise [in \$T_v\$](#) ($R^2 \approx 0.80$ with SonicW), although to a lesser extent than LidarN. No clear directional dependence is observed: despite the higher turbulence levels in southerly flow, there is no corresponding increase in measurement uncertainties in this sector (Figure 5).

3.2 Co-coherence validation

Figure 6 presents the ensemble-averaged one-point power spectral densities (PSDs), co-coherence, and quad-coherence of the along-beam velocity component for northerly winds (330° – 360° , 27 samples) and southerly winds (120° – 180° , 46 samples). For the northerly winds, the co-coherence between SonicW and SonicE is nearly identical to that obtained between SonicE and LidarW, indicating that LidarW reproduces the ~~measured turbulence coherence~~ [estimated turbulence co-coherence](#) under favourable conditions. The co-coherence involving LidarN is systematically lower at all frequencies, despite similar separation distances, which is attributed to measurement noise in the LidarN data. The one-point spectra provide further insight into this behaviour. In Figure 6(a), the spectra from LidarW exhibit a steeper decay than the classical $-5/3$ slope at high wavenumbers ($k > 0.1 \text{ m}^{-1}$), consistent with probe-volume averaging [14] and indicative of a low measurement noise. By contrast, the spectrum of LidarN shows a less steep decay, similar to that of the sonic anemometers, suggesting contamination by measurement noise rather than improved resolution of small-scale turbulence. This ~~uncorrelated~~ noise leads to a systematic underestimation of the co-coherence.

For southerly flow (panels d,e,f in [fig. 6](#) [Figure 6](#)), the ensemble-averaged co-coherence shows systematic discrepancies between the SonicW–SonicE and SonicE–LidarW pairs. These discrepancies are likely associated with [the possible combined effect of](#) higher turbulence levels ~~and~~ [in-](#)

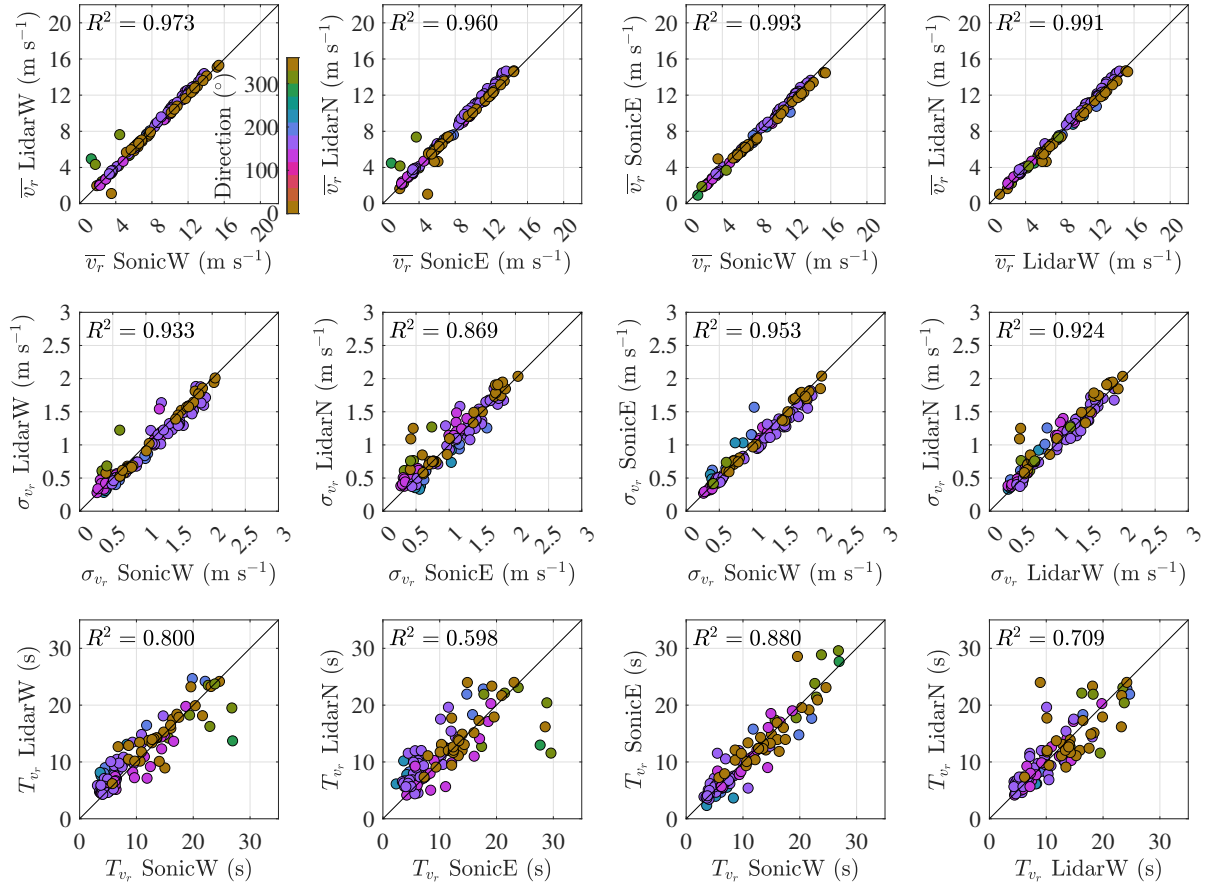


Figure 5. Comparison of lidar- and sonic-derived along-beam statistics for all available records. Top panels: mean along-beam velocity $\bar{v}_r$. Middle panels: standard deviation σ_{v_r} . Bottom panels: Integral time scale T_{v_r} . Data collected between 17 March 2020 and 29 March 2020 (111 samples).

creased flow heterogeneity, [local terrain effect and potentially different measurement conditions](#), which increase the measurement uncertainty within the lidar probe volume. They are even larger for pairs involving LidarN, reflecting the higher noise level in its measurements. The quad-coherence remains close to zero for northerly flow, with no clear difference between the SonicW–SonicE and SonicE–LidarW pairs. For southerly flow, the quad-coherence also shows no clear difference between these two pairs. However, a maximum in the quad-coherence is visible around $k \approx 0.01 \text{ m}^{-1}$, consistent with the negative co-coherence observed at a wave number close to that for the negative co-coherence. This feature indicates a non-zero phase component of the [coherence-co-coherence](#), consistent with asymmetric coherent flow structures under southerly flow conditions.

These results demonstrate that synchronised long-range pulsed Doppler lidars can reliably [measure-be used to estimate](#) horizontal turbulence co-coherence when the measurement noise is low. They also show that high noise levels can significantly bias [coherence-co-coherence](#) estimates. A practical implication is that reliable co-coherence estimates are obtained when probe-volume averaging is clearly visible in the PSD, as this indicates a sufficiently high signal-to-noise ratio.

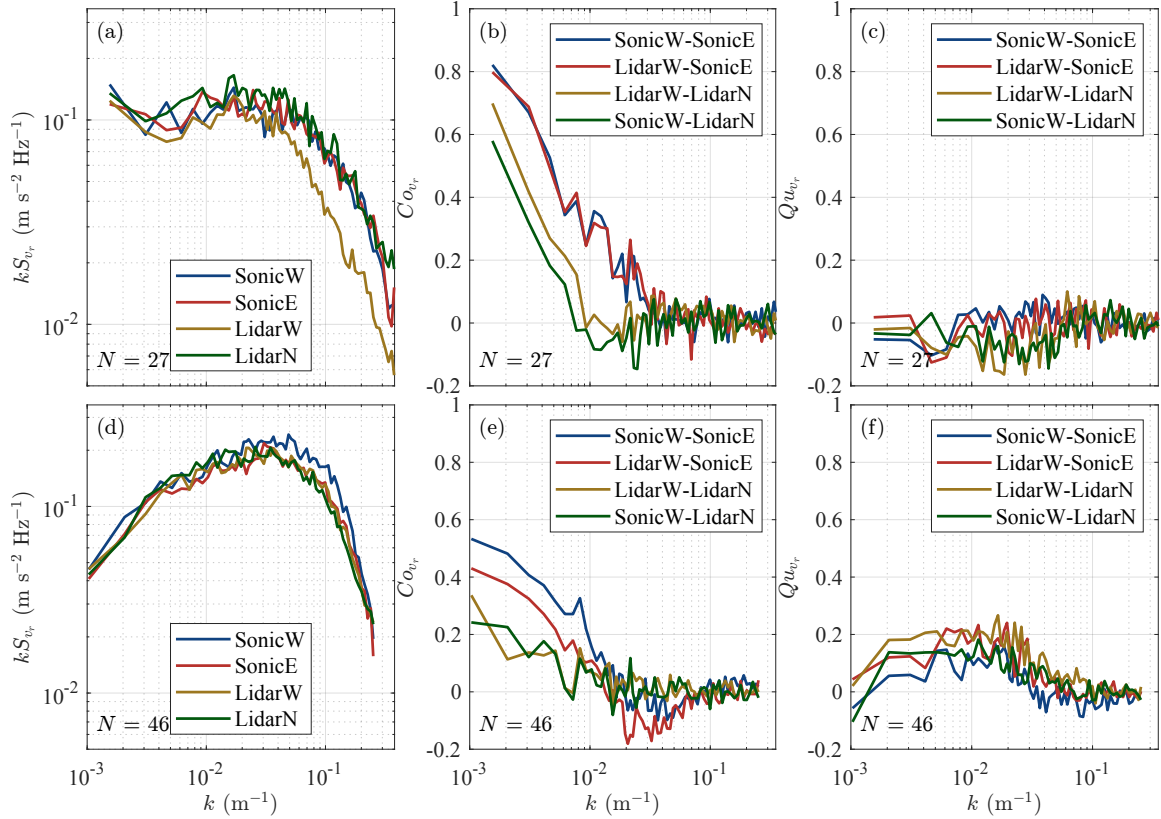


Figure 6. Ensemble-averaged one-point power spectral densities (a, d), co-coherence (b, e) and ~~quad-coherence~~ quad-coherence (c, f) of the along-beam velocity component for 50-minute time series: 27 cases under northerly winds (330° – 360° ; a, b, c) and 46 cases under southerly winds (120° – 180° ; d, e, f). The curves in panels b, c, e and f compare sonic–sonic, lidar–sonic, and lidar–lidar co-coherence estimates at similar separation distances.

3.3 Toward practical measurements of turbulence coherence

This study demonstrates that synchronised scanning Doppler wind lidars can be used to estimate turbulence co-coherence under favourable conditions, but practical implementation remains challenging. The sensitivity of ~~coherence~~ co-coherence estimates to measurement noise may require redundancy, for example, through the deployment of multiple lidar units, which increases both cost and logistical complexity. In addition, small beam misalignments can lead to significant errors, particularly at larger distances from the instruments [7]. Accurate measurements require lidar beams aligned with the mean wind direction, achieved either through dynamic alignment [7] or selective filtering of data when wind direction and beam azimuth are nearly aligned.

In practice, suitable conditions include sufficiently strong winds, a wind direction not perpendicular to the lidar beams when horizontal separations are of interest, a fixed measurement platform, adequate aerosol content, and approximately homogeneous flow, i.e. outside the lee of terrain or obstacles. Restricting the analysis to narrow wind direction sectors may substantially reduce data availability, while low wind conditions are of limited relevance for structural loading applications. Single-lidar scanning strategies, such as narrow-azimuth plan position indicator (PPI) scans [11, 14], offer a more practical alternative but at the expense of lower effective sampling frequencies.

Measurement uncertainty increases with distance from the lidar due to both beam misalign-

ment and decreasing signal-to-noise ratio. Small angular errors translate into significant lateral offsets at long range (e.g. about 9 m at 500 m for a 1° misalignment, and about 1.7 m at 1 km for 0.1°), biasing the estimated separation distance and thus the co-coherence. Previous results from the COTUR campaign indicate that an angular accuracy on the order of 0.1° is required for reliable measurements at kilometre scales [7]. The effective range of a WindCube 100S is typically limited to about 1.5 km to 2 km. Although longer-range systems can extend this distance, they rely on larger probe volumes, which further limit the accuracy of turbulence measurements. Overall, these constraints highlight a trade-off between measurement quality, spatial and temporal resolution, and data availability, suggesting that simpler lidar configurations may be more robust for long-term analysis of the turbulence ~~coherence~~co-coherence.

Emerging drone-based measurement techniques provide a promising alternative for studying turbulence coherence offshore. Large multicopter platforms can carry 3D sonic anemometers for more than 20 min per flight, enabling in-situ measurements of turbulence and atmospheric stability at locations not reachable by masts [20]. Swarms of smaller drones could also be deployed to estimate the ~~coherence~~co-coherence and quad-coherence [21], although they should be complemented by near-surface measurements to properly characterise atmospheric stability. Since atmospheric stability strongly influences turbulence coherence [22], the use of in situ reference measurements remains essential, regardless of whether lidar or drone-based systems are employed.

4 Conclusions

This study provides one of the first dedicated validations of horizontal turbulence ~~co-coherence~~measured-estimated using dual synchronised long-range pulsed Doppler wind lidars. Two WindCube 100S lidars, denoted LidarN and LidarW, operated in fixed line-of-sight mode, and their measurements were compared with data from two 3D sonic anemometers separated by 24 m. One-point statistics showed good agreement, with $R^2 > 0.96$ for the mean along-beam velocity and $R^2 \approx 0.87\text{--}0.93$ for its standard deviation. The integral time scale exhibited larger scatter than the standard deviation, as expected, and proved useful to diagnose measurement noise, which was larger for LidarN than LidarW.

The lidar-derived ~~co-coherence~~co-coherence closely matched the sonic reference under favourable (northerly) conditions, demonstrating that dual-lidar configurations can capture horizontal turbulence ~~coherence~~co-coherence. Under southerly flow, characterised by higher turbulence intensity and increased flow heterogeneity, larger discrepancies were observed, reflecting an increased measurement uncertainty. Significant measurement noise in LidarN led to a systematic underestimation of the co-coherence across all frequencies. The analysis further showed that probe-volume averaging, visible as a steep spectral decay at high wavenumbers, is a useful indicator of low-noise conditions.

These results confirm that scanning Doppler wind lidars can reliably ~~measure~~be used to estimate turbulence co-coherence when beam alignment is accurate, flow conditions are sufficiently homogeneous, and measurement noise is controlled. In the present experiment, the short lidar-mast distance (less than ~~150 m~~160 m) and dedicated hard-target tests ensured negligible alignment uncertainty. Previous results from the COTUR campaign indicate that an angular accuracy of about 0.1° is required at longer ranges [7]. The present validation, therefore, represents near-optimal conditions under which dual-lidar systems provide a practical alternative to offshore masts for studying horizontal turbulence ~~coherence~~co-coherence.

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