Measuring velocity variances with dual-Doppler scanning lidars

Alfredo Peña, Jakob Mann and Nikola Vasiljevic

DTU Wind Energy, Risø campus – Department of Wind Energy

WESC 2019

Cork, Ireland

Innovation Fund Denmark

RECAS
Reduced Assessment Time

Motivation

- scanning lidars are used in nearly all wind-like applications

Motivation

- scanning lidars are used in nearly all wind-like applications
- dual-Doppler system: avoid the assumption of homogeneity (but others), wind energy is mostly concerned in the horizontal components, less expensive than three+, not trivial to measure with multi-lidars

Motivation

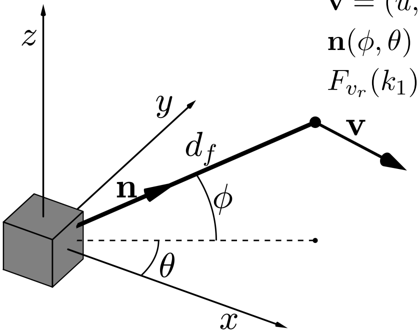
- scanning lidars are used in nearly all wind-like applications
- dual-Doppler system: avoid the assumption of homogeneity (but others), wind energy is mostly concerned in the horizontal components, less expensive than three+, not trivial to measure with multi-lidars
- main systems used during the Perdigão and Alaiz experiments in NEWA

Motivation

- scanning lidars are used in nearly all wind-like applications
- dual-Doppler system: avoid the assumption of homogeneity (but others), wind energy is mostly concerned in the horizontal components, less expensive than three+, not trivial to measure with multi-lidars
- main systems used during the Perdigão and Alaiz experiments in NEWA
- we want to know how 'well' we measure turbulence with such configuration

Motivation

- scanning lidars are used in nearly all wind-like applications
- dual-Doppler system: avoid the assumption of homogeneity (but others), wind energy is mostly concerned in the horizontal components, less expensive than three+, not trivial to measure with multi-lidars
- main systems used during the Perdigão and Alaiz experiments in NEWA
- we want to know how 'well' we measure turbulence with such configuration



$$\mathbf{v} = (u, v, w)$$

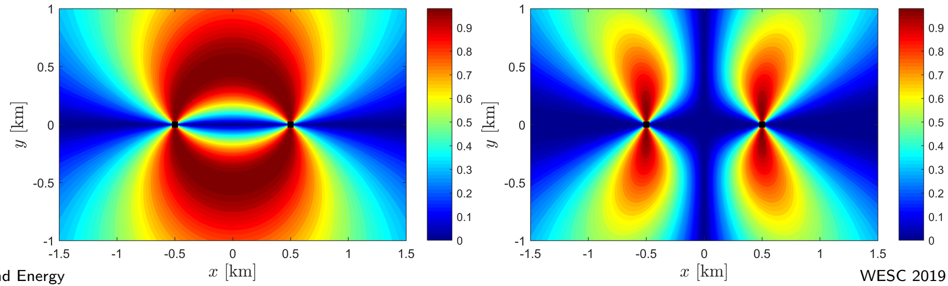
$$\mathbf{n}(\phi, \theta) = (\cos\theta\cos\phi, \sin\theta\cos\phi, \sin\phi)$$

$$F_{v_r}(k_1) = n_i n_j \iint |\hat{\varphi}(\mathbf{k}\cdot\mathbf{n})|^2 \, \Phi_{ij}(\mathbf{k}) dk_2 dk_3$$

Direct method: $w = 0$, $\langle u'v' \rangle = 0$ – use of Doppler spectra for unfiltered $\sigma^2_{v_r}$

$$\underbrace{\begin{bmatrix} v_{r_1} \\ v_{r_2} \end{bmatrix}}_{\mathbf{vr}} = \underbrace{\begin{bmatrix} \cos\theta_1 \cos\phi_1 & \sin\theta_1 \cos\phi_1 \\ \cos\theta_2 \cos\phi_2 & \sin\theta_2 \cos\phi_2 \end{bmatrix}}_{\mathbf{M}} \underbrace{\begin{bmatrix} u \\ v \end{bmatrix}}_{\mathbf{v}}$$

$$\underbrace{\begin{bmatrix} \sigma^2_{v_{r_1}} \\ \sigma^2_{v_{r_2}} \end{bmatrix}}_{\mathbf{S}} = \underbrace{\begin{bmatrix} \cos^2\theta_1 \cos^2\phi_1 & \sin^2\theta_1 \cos^2\phi_1 \\ \cos^2\theta_2 \cos^2\phi_2 & \sin^2\theta_2 \cos^2\phi_2 \end{bmatrix}}_{\mathbf{P}} \underbrace{\begin{bmatrix} \sigma^2_u \\ \sigma^2_v \end{bmatrix}}_{\mathbf{Q}}$$



Indirect method – biases estimation accounting for filtering of $\sigma^2_{v_r}$

- Reynolds stresses can be computed as

$$\langle u_i' u_j' \rangle = N_{i\alpha} \langle v'_{r,\alpha} v'_{r,\beta} \rangle N_{j\beta}$$

$$\langle v'_{r,\alpha} v'_{r,\beta} \rangle = n_i^\alpha n_j^\beta \int \hat{\varphi}(\mathbf{k} \cdot \mathbf{n}^\alpha) \hat{\varphi}(\mathbf{k} \cdot \mathbf{n}^\beta) \Phi_{ij}(\mathbf{k}) d\mathbf{k}, \qquad \text{(no summation over } \alpha \text{ and } \beta\text{)}$$

is the covariance matrix of radial velocities, being α and β subscripts indicating the lidar numbering. For a dual-Doppler system:

$$\mathbf{N} = \begin{bmatrix} \cos\theta_1 \cos\phi_1 & \sin\theta_1 \cos\phi_1 & \sin\phi_1 \\ \cos\theta_2 \cos\phi_2 & \sin\theta_2 \cos\phi_2 & \sin\phi_2 \end{bmatrix}^{-1}$$

Indirect method – biases estimation accounting for filtering of $\sigma^2_{v_r}$

- Reynolds stresses can be computed as

$$\langle u_i' u_j' \rangle = N_{i\alpha} \langle v_{r,\alpha}' v_{r,\beta}' \rangle N_{j\beta}$$

$$\langle v_{r,\alpha}' v_{r,\beta}' \rangle = n_i^{\alpha} n_j^{\beta} \int \hat{\varphi}(\mathbf{k} \cdot \mathbf{n}^{\alpha}) \hat{\varphi}(\mathbf{k} \cdot \mathbf{n}^{\beta}) \Phi_{ij}(\mathbf{k}) d\mathbf{k}, \qquad \text{(no summation over } \alpha \text{ and } \beta\text{)}$$

is the covariance matrix of radial velocities, being α and β subscripts indicating the lidar numbering. For a dual-Doppler system:

$$\mathbf{N} = \begin{bmatrix} \cos\theta_1 \cos\phi_1 & \sin\theta_1 \cos\phi_1 & \sin\phi_1 \\ \cos\theta_2 \cos\phi_2 & \sin\theta_2 \cos\phi_2 & \sin\phi_2 \end{bmatrix}^{-1}$$

- for $\hat{\varphi}(\mathbf{k} \cdot \mathbf{n}) \approx 1$ and three beams geometry dependencies compensate

Indirect method – biases estimation accounting for filtering of $\sigma^2_{v_r}$

- Reynolds stresses can be computed as

$$\langle u_i' u_j' \rangle = N_{i\alpha} \langle v'_{r,\alpha} v'_{r,\beta} \rangle N_{j\beta}$$

$$\langle v'_{r,\alpha} v'_{r,\beta} \rangle = n_i^\alpha n_j^\beta \int \hat{\varphi}(\mathbf{k}\cdot\mathbf{n}^\alpha)\hat{\varphi}(\mathbf{k}\cdot\mathbf{n}^\beta)\Phi_{ij}(\mathbf{k})d\mathbf{k}, \qquad \text{(no summation over } \alpha \text{ and } \beta\text{)}$$

  is the covariance matrix of radial velocities, being α and β subscripts indicating the lidar numbering. For a dual-Doppler system:

$$\mathbf{N} = \begin{bmatrix} \cos\theta_1 \cos\phi_1 & \sin\theta_1 \cos\phi_1 & \sin\phi_1 \\ \cos\theta_2 \cos\phi_2 & \sin\theta_2 \cos\phi_2 & \sin\phi_2 \end{bmatrix}^{-1}$$

- for $\hat{\varphi}(\mathbf{k}\cdot\mathbf{n}) \approx 1$ and three beams geometry dependencies compensate
- for a dual-Doppler system the ‘complexity’ is in the computation of $\langle v'_{r,1} v'_{r,2} \rangle$

Indirect method – biases estimation accounting for filtering of $\sigma^2_{v_r}$

- Reynolds stresses can be computed as

$$\langle u_i' u_j' \rangle = N_{i\alpha} \langle v'_{r,\alpha} v'_{r,\beta} \rangle N_{j\beta}$$

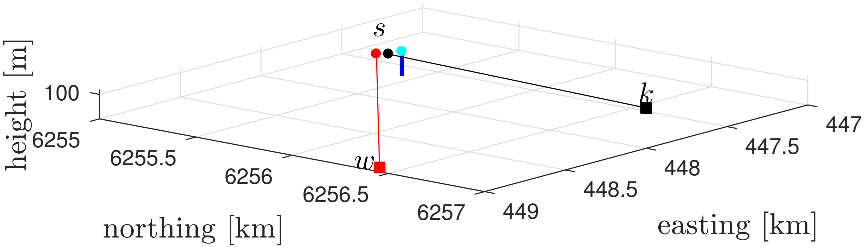
$$\langle v'_{r,\alpha} v'_{r,\beta} \rangle = n_i^\alpha n_j^\beta \int \hat{\varphi}(\mathbf{k} \cdot \mathbf{n}^\alpha) \hat{\varphi}(\mathbf{k} \cdot \mathbf{n}^\beta) \Phi_{ij}(\mathbf{k}) d\mathbf{k}, \qquad \text{(no summation over } \alpha \text{ and } \beta\text{)}$$

  is the covariance matrix of radial velocities, being α and β subscripts indicating the lidar numbering. For a dual-Doppler system:

$$\mathbf{N} = \begin{bmatrix} \cos\theta_1 \cos\phi_1 & \sin\theta_1 \cos\phi_1 & \sin\phi_1 \\ \cos\theta_2 \cos\phi_2 & \sin\theta_2 \cos\phi_2 & \sin\phi_2 \end{bmatrix}^{-1}$$

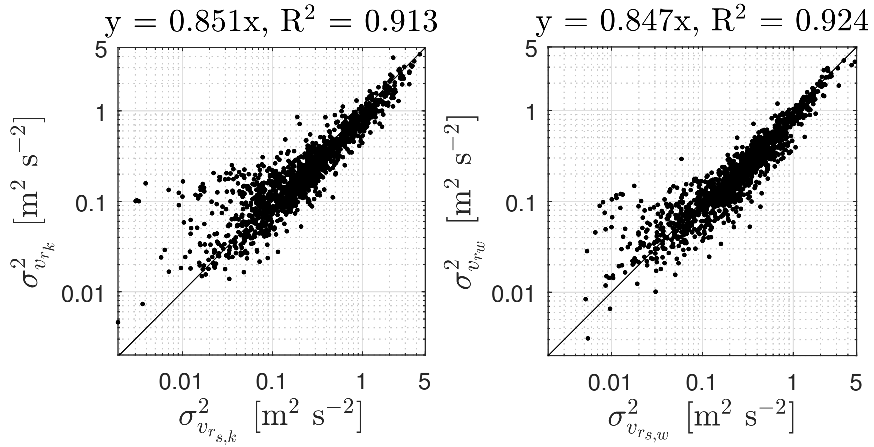
- for $\hat{\varphi}(\mathbf{k} \cdot \mathbf{n}) \approx 1$ and three beams geometry dependencies compensate
- for a dual-Doppler system the ‘complexity’ is in the computation of $\langle v'_{r,1} v'_{r,2} \rangle$
- for $\hat{\varphi}(\mathbf{k} \cdot \mathbf{n}) \approx 1$ and two beams, a bias is inherent... unless

The ssvsdd experiment

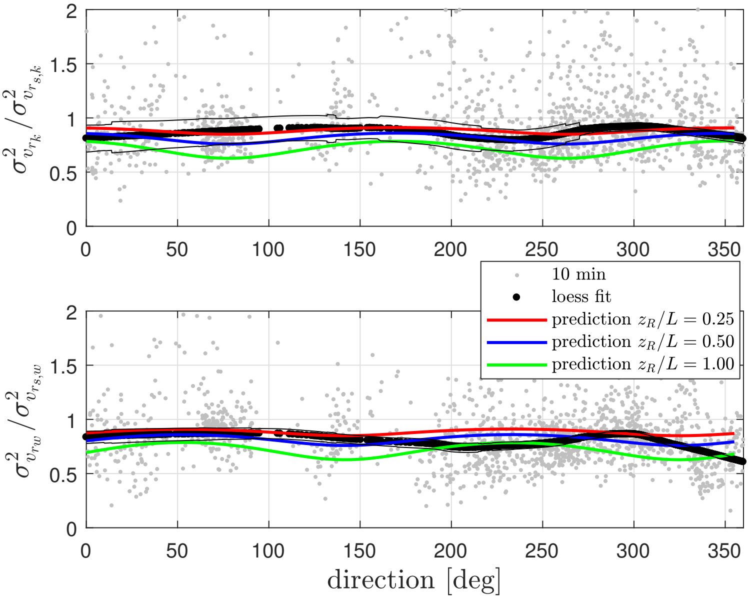


- 15 days of concurrent data of 2 WindScanners (200 ns) accumulating spectra for 500 ms
- elevations of 5 and 3 deg and ranges of 1.1 and 1.6 km
- 10-min statistics, –25 dB<CNR<–5 dB, 1000 scans per 10-min
- 1939 10-min periods for analysis

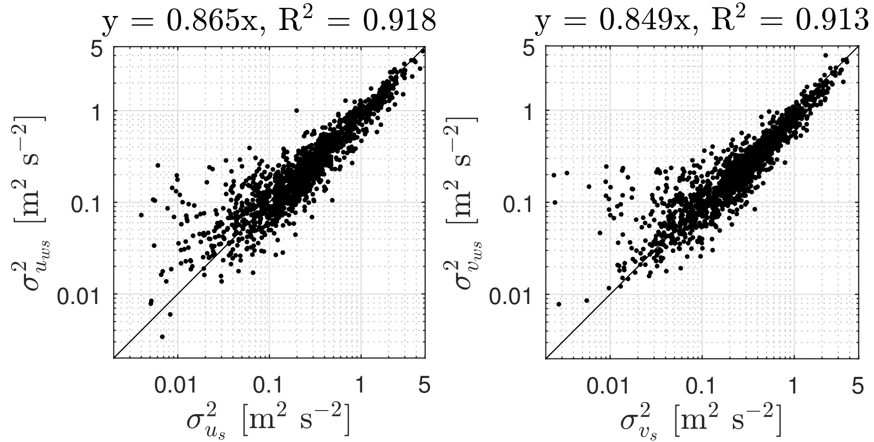
Radial velocity variance



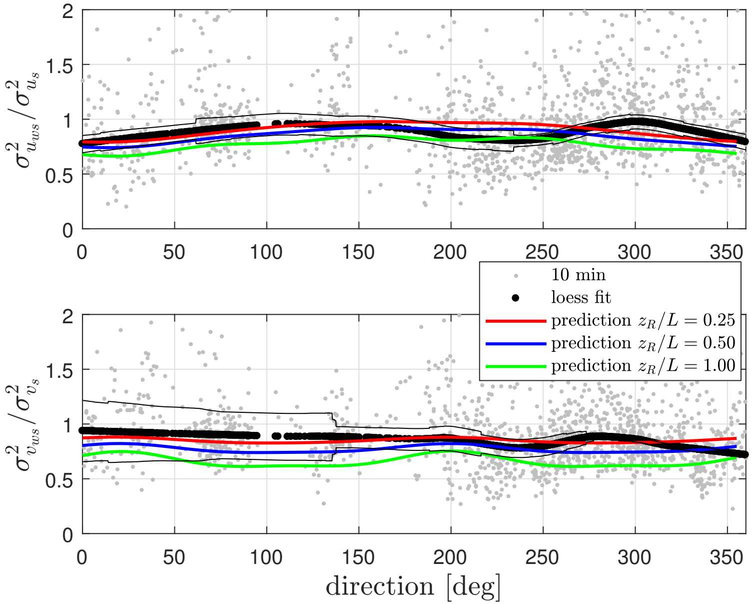
Radial velocity variance



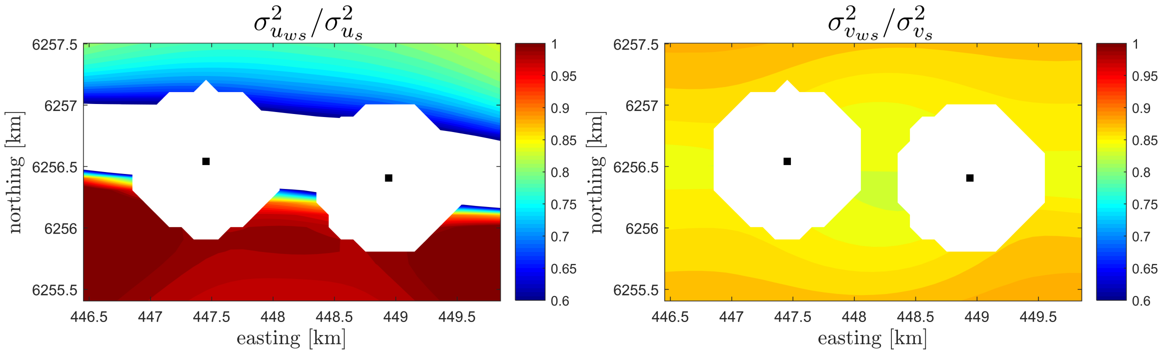
Velocity component variances



Velocity component variances



Spatial variation of biases – 100 m, 180 deg wind, $z_R/L = 0.25$



Conclusions and perspectives

- by using a dual-Doppler lidar system, velocity component variances from reconstructed velocities are biased

Conclusions and perspectives

- by using a dual-Doppler lidar system, velocity component variances from reconstructed velocities are biased
- in such a system, bias depends on both turbulence characteristics and scanning configuration relative to the mean wind

Conclusions and perspectives

- by using a dual-Doppler lidar system, velocity component variances from reconstructed velocities are biased
- in such a system, bias depends on both turbulence characteristics and scanning configuration relative to the mean wind
- we are able to accurately estimate this bias

Conclusions and perspectives

- by using a dual-Doppler lidar system, velocity component variances from reconstructed velocities are biased
- in such a system, bias depends on both turbulence characteristics and scanning configuration relative to the mean wind
- we are able to accurately estimate this bias
- alternative is to estimate the unfiltered radial velocity variance of both lidars... singular system!

Conclusions and perspectives

- by using a dual-Doppler lidar system, velocity component variances from reconstructed velocities are biased
- in such a system, bias depends on both turbulence characteristics and scanning configuration relative to the mean wind
- we are able to accurately estimate this bias
- alternative is to estimate the unfiltered radial velocity variance of both lidars... singular system!
- we want to repeat exercise at Perdigão and Alaiz for the ridge scans

Conclusions and perspectives

- by using a dual-Doppler lidar system, velocity component variances from reconstructed velocities are biased
- in such a system, bias depends on both turbulence characteristics and scanning configuration relative to the mean wind
- we are able to accurately estimate this bias
- alternative is to estimate the unfiltered radial velocity variance of both lidars... singular system!
- we want to repeat exercise at Perdigão and Alaiz for the ridge scans
- can we improve our turbulence modeling based on those ridge scans?

Thanks for your attention!