# Turbulence characterization from a forward-looking nacelle lidar

**Alfredo Peña**, Jakob Mann and Nikolay K. Dimitrov

DTU Wind Energy, Risø campus – Department of Wind Energy

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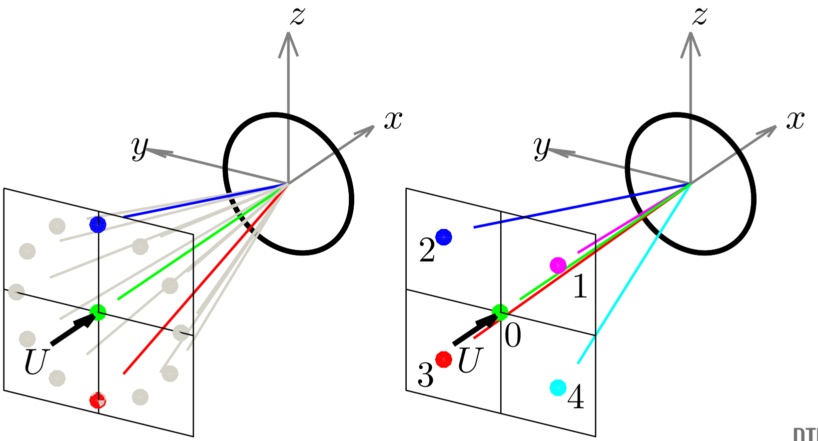
# Forward-looking nacelle lidars



## M1: Lidar radial velocity spectra, filtered $\sigma^2_{v_r}$

- From Mann et al. (2009):

$$F_v(k_1) = n_i n_j \iint \left|\hat{\phi}(\boldsymbol{k}\cdot\boldsymbol{n})\right|^2 \Phi_{ij}(\boldsymbol{k}) dk_2 dk_3, \quad (1)$$

where $\boldsymbol{n} = (-\cos\varphi, \sin\varphi\cos\theta, \sin\varphi\sin\theta)$

- Weighting function of CW lidar:

$$\phi(s) = \frac{1}{\pi}\frac{z_R}{z_R^2 + s^2} \Leftrightarrow \hat{\phi}(k_1) = \exp(-|k_1|z_R) \quad (2)$$

- Weigthing function of a pulsed lidar:

$$\phi(s) = \frac{z_R - |s|}{z_R^2} \Leftrightarrow \hat{\phi}(k_1) = \mathrm{sinc}^2(k_1 z_R/2) \quad (3)$$

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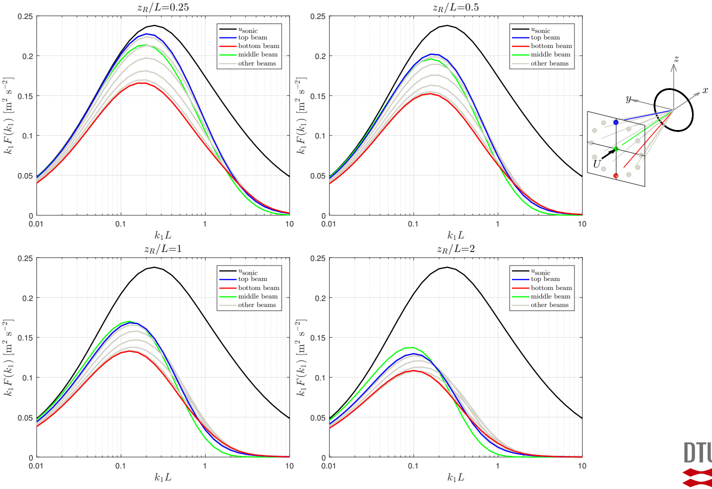
# M1: CW lidar, $\Gamma = 3$, $\alpha\varepsilon^{2/3} = 0.1$, $\varphi = 15^\circ$



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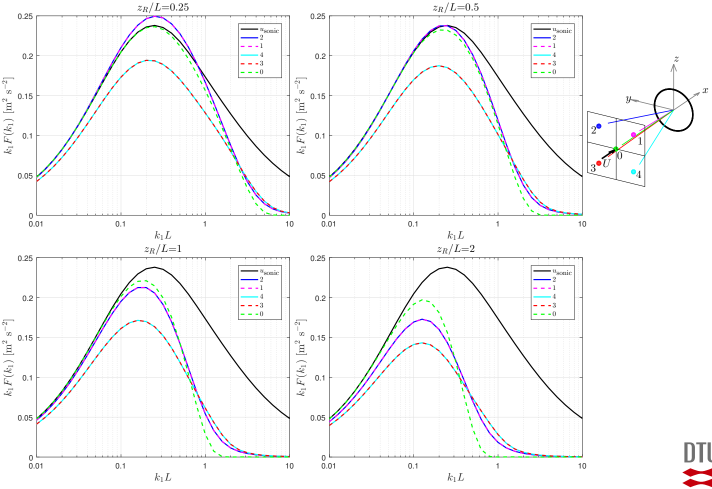
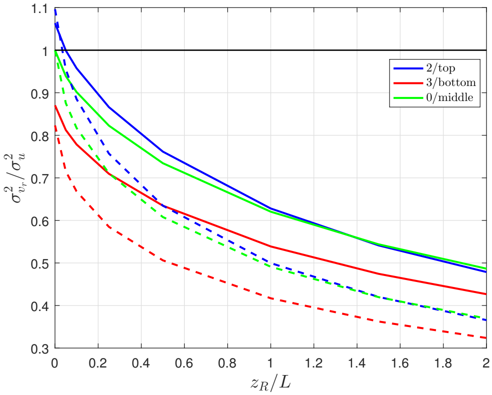


# M1: For $\Gamma = 3$, $\varphi = 15^\circ$

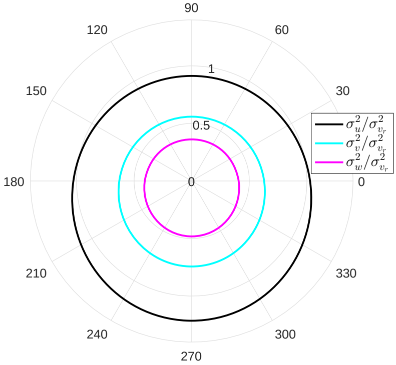
pulsed lidar in solid lines and CW lidar in dashed lines



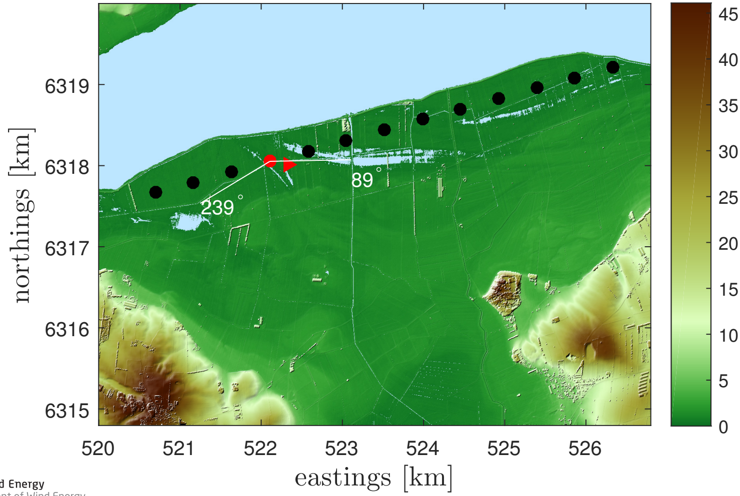
# M2: Doppler spectra info, $z_R/L = 0$ (no filtering), no turbulence model, unfiltered $\sigma^2_{v_r}$

Assuming homogeneous turbulence within the rotor area:

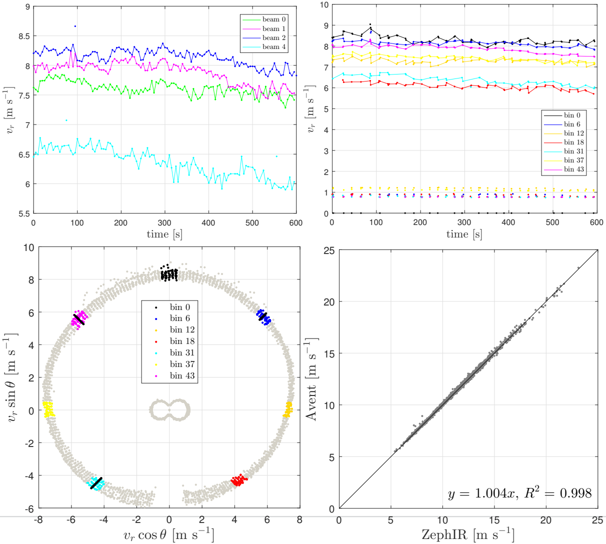
$$\sigma^2_{v_r}(\theta) =$$
$$\sigma^2_u \cos^2\varphi + \sigma^2_v \sin^2\varphi \cos^2\theta + \sigma^2_w \sin^2\varphi \sin^2\theta - 2\overline{u'w'} \cos\varphi \sin\varphi \sin\theta$$



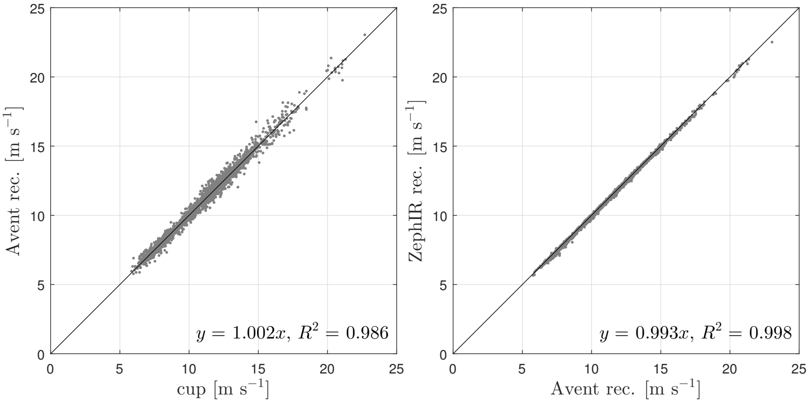
# Nørrekær Enge wind farm



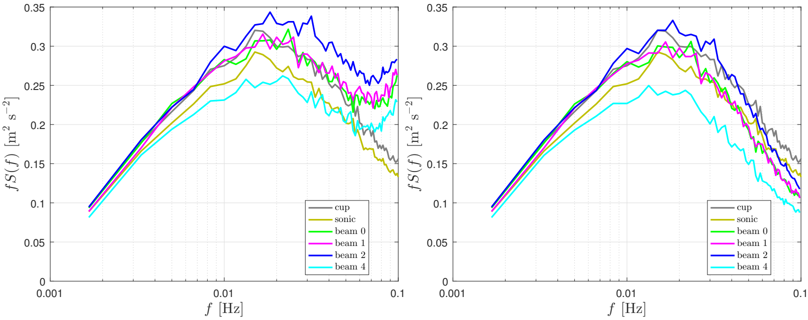
# 10-min time-series examples



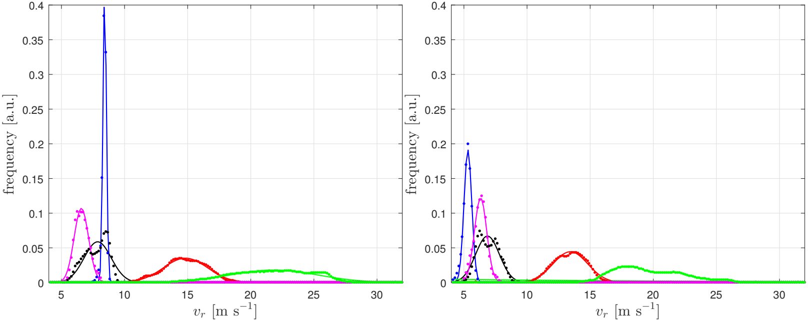
# Wind reconstruction (for spectra and 18-s filtered variance analysis)



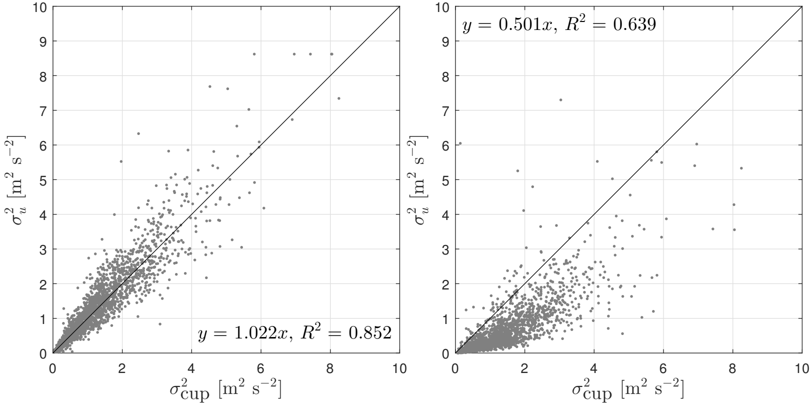
# raw vs. noise-filtered velocity spectra (for M2)



# M2: $\sigma^2_{v_{r,unf}}$ Doppler spectra: bin 0 (left) and bin 31 (right)



# M2: Unfiltered vs 18-s based filtered variances

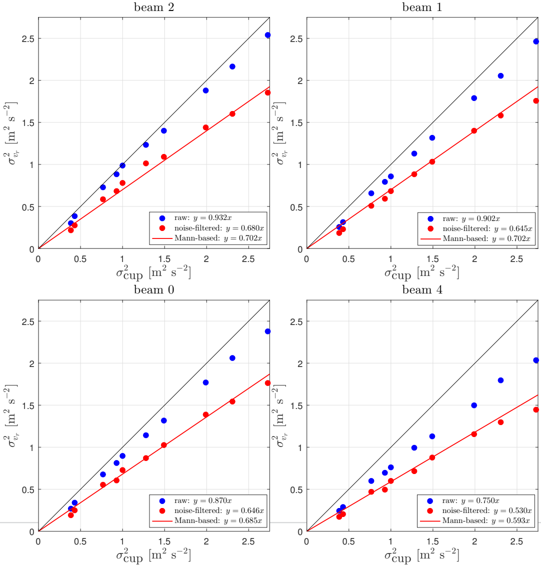



$$\sigma_{v_r}^2(\theta) = \sigma_u^2 \cos^2\varphi + \sigma_v^2 \sin^2\varphi \cos^2\theta + \sigma_w^2 \sin^2\varphi \sin^2\theta$$
$$-2\langle u'w'\rangle \cos\varphi \sin\varphi \sin\theta$$

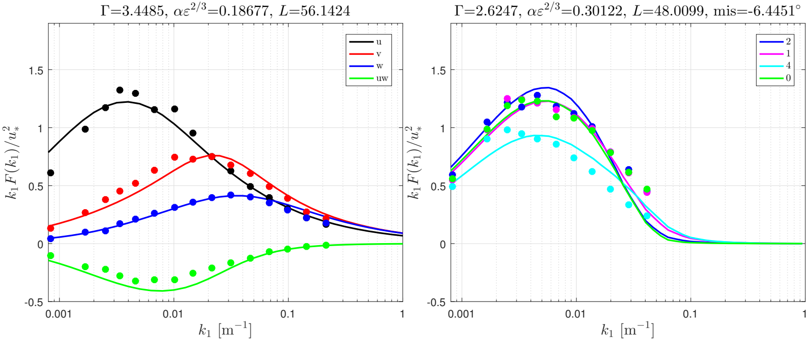
# Stability and wind speed ranges

| class | $z/L_0$ | no. of 10-min samples | $\langle z/L_O \rangle$ | $\langle U \rangle$ [m s$^{-1}$] | $\langle u_* \rangle$ [m s$^{-1}$] |
|---|---|---|---|---|---|
| stability 1 | $-0.1$–0.1 | 225 | 0.0625 | 12.75 | 0.68 |
| stability 2 | 0.1–0.2 | 629 | 0.1489 | 12.54 | 0.61 |
| stability 3 | 0.2–0.3 | 350 | 0.2435 | 11.34 | 0.48 |
| stability 4 | 0.3–0.4 | 225 | 0.3475 | 10.71 | 0.42 |
| stability 5 | 0.4–0.5 | 153 | 0.4457 | 10.02 | 0.35 |
| class | $U$ [m s$^{-1}$] | no. of 10-min samples | $\langle U \rangle$ [m s$^{-1}$] | $\widetilde{z/L_O}$ | $\langle u_* \rangle$ [m s$^{-1}$] |
| speed 1 | 5–7 | 93 | 6.65 | 0.5084 | 0.21 |
| speed 2 | 7–9 | 516 | 7.98 | 0.7196 | 0.23 |
| speed 3 | 9–11 | 506 | 10.07 | 0.3684 | 0.37 |
| speed 4 | 11–13 | 741 | 11.94 | 0.2133 | 0.52 |
| speed 5 | 13–15 | 278 | 13.82 | 0.1402 | 0.64 |

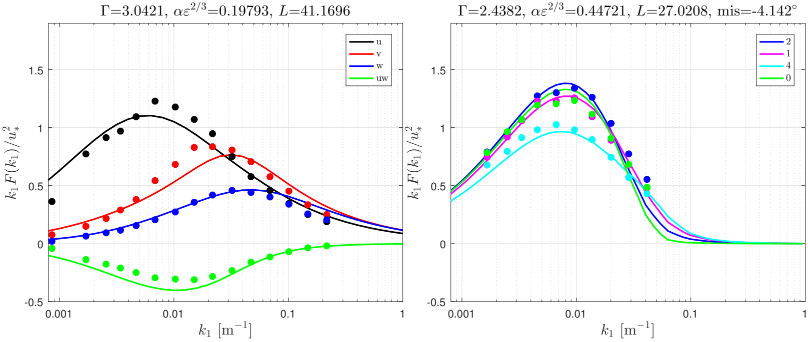
# M1: Atmospheric stability and wind speed ranges



# M1: Stability 1



# M1: Stability 2

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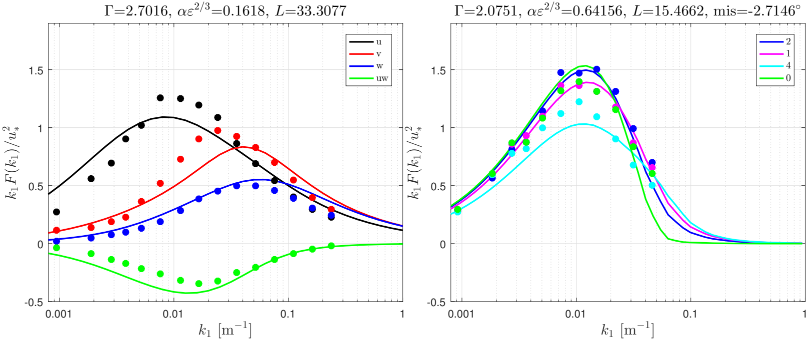
# M1: Stability 3

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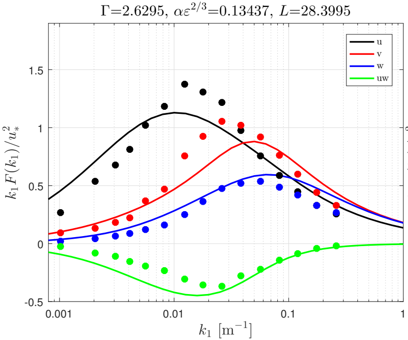
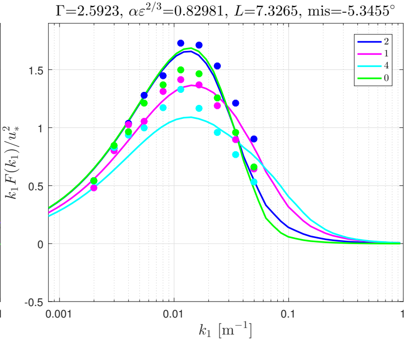
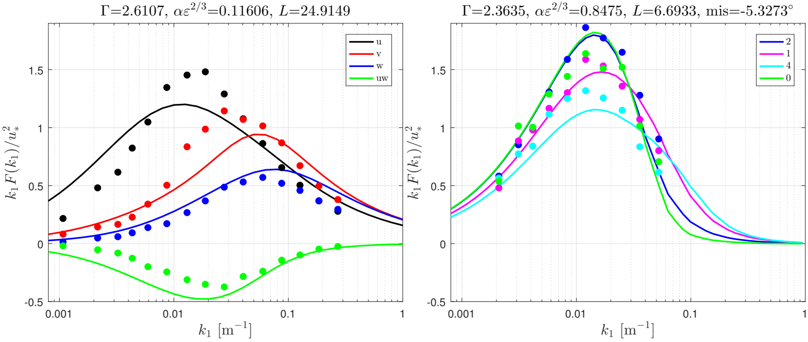
# M1: Stability 4

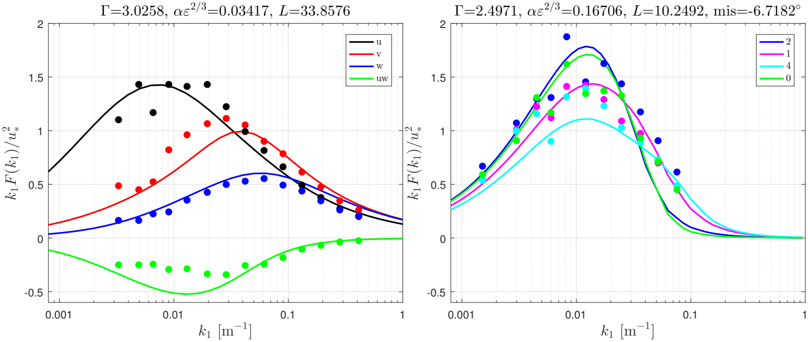


# M1: Stability 5

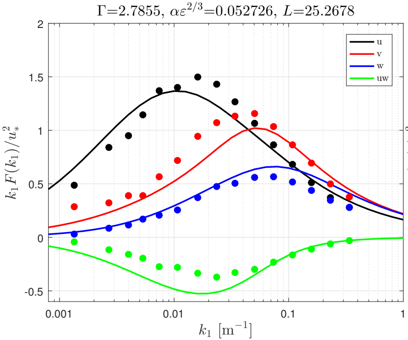


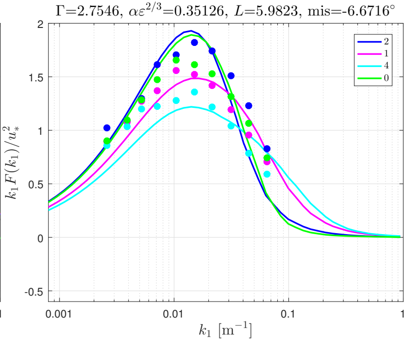
# M1: Speed 1



Γ=3.0258, αε^{2/3}=0.03417, L=33.8576
k_1 F(k_1)/u_*^2
k_1 [m^{-1}]
u
v
w
uw
Γ=2.4971, αε^{2/3}=0.16706, L=10.2492, mis=-6.7182°
k_1 F(k_1)/u_*^2
k_1 [m^{-1}]
2
1
4
0

# M1: Speed 2

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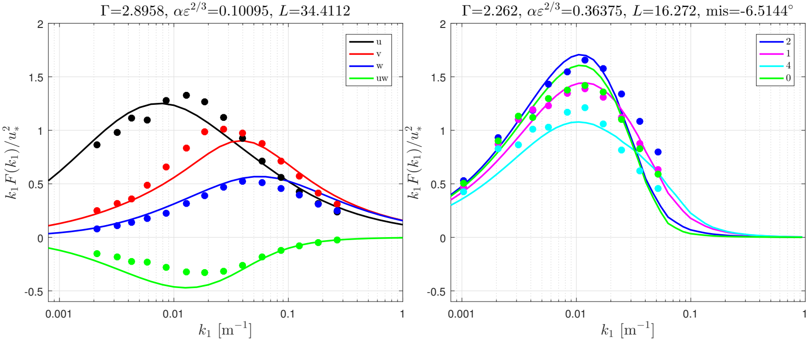
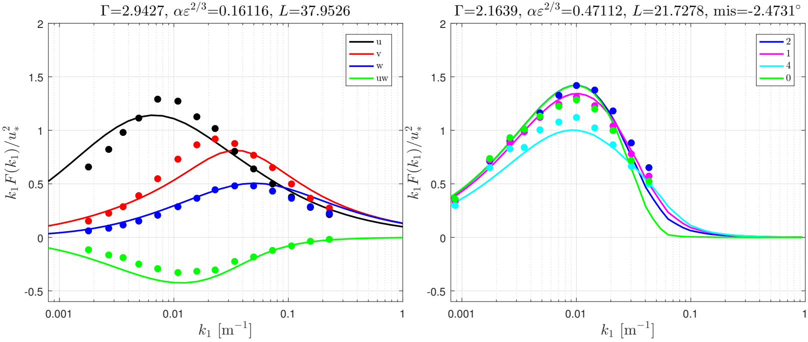
# M1: Speed 3

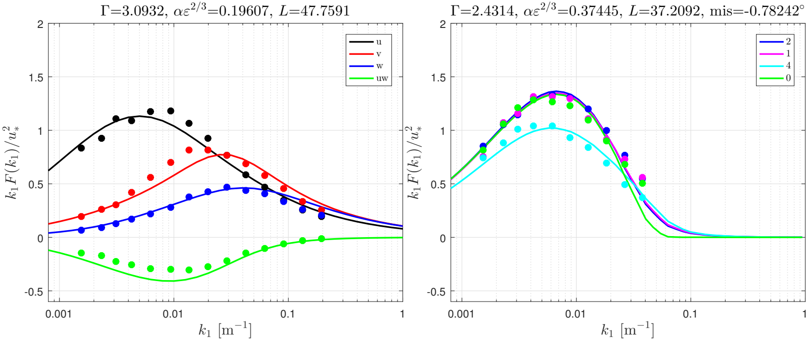


Γ=2.8958, $\alpha\varepsilon^{2/3}$=0.10095, $L$=34.4112
Γ=2.262, $\alpha\varepsilon^{2/3}$=0.36375, $L$=16.272, mis=-6.5144°
$k_1 F(k_1)/u_*^2$
$k_1$ [m$^{-1}$]
u
v
w
uw
2
1
4
0
0.001
0.01
0.1
1
2
1.5
1
0.5
0
-0.5

# M1: Speed 4


Γ=2.9427, αε^{2/3}=0.16116, L=37.9526
Γ=2.1639, αε^{2/3}=0.47112, L=21.7278, mis=-2.4731°
u
v
w
uw
2
1
4
0
k_1 F(k_1)/u_*^2
k_1 [m^{-1}]
2
1.5
1
0.5
0
-0.5
0.001
0.01
0.1
1

# M1: Speed 5

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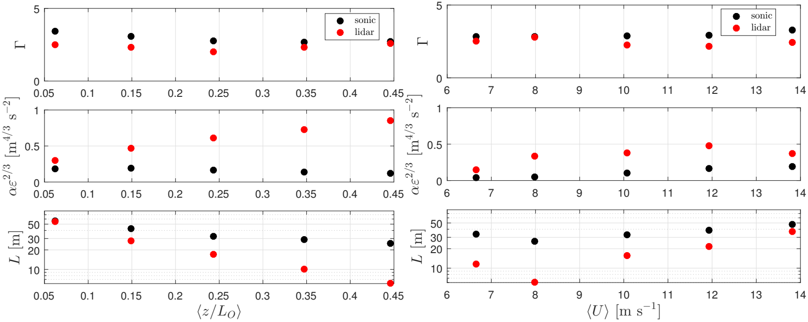
# M1: Mann parameters behaviour



# Conclusions

- Using the 10-min Doppler LOS spectrum, we are able to derive unfiltered $\sigma_{v_r}^2$
- Comparison with cup reveals 2% bias for $\sigma_u^2$
- Variances from noise-filtered lidar LOS spectra are well predicted by the Mann and spatial averaging lidar models
- Mann parameters derived from lidar LOS spectra agree with those from a sonic under high wind and neutral conditions
- For other conditions, this could be better done by increasing cone angle

# Thank you for the attention!

Funded by Innovation Fund, Denmark, to the UniTTe project

More details in: Peña A., Mann J. and Dimitrov N. (2017): Turbulence characterization from a forward-looking nacelle lidar. Wind Energ. Sci. 2:133–152