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Lidar Scanning of Momentum Flux in the Marine Boundary Layer

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Lidar scanning of momentum flux in the marine boundary layer

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Abstract

A method to measure the momentum flux by a conical scanning wind lidar is investigated. For near-neutral conditions, lidar observations of wind speed performed over the North Sea on the platform at the Horns Rev wind farm compare well to the cup measurements, whereas the lidar momentum flux is found to be attenuated due to the filtering effect when compared to bulk-derived estimations from cups. However, the filtering effect from the spatial-averaging measurement volume can be well-predicted using the spectral tensor of turbulence.

Theory

The laser points in the direction

$$\boldsymbol{n}(\theta) = (\sin\phi\cos\theta, \sin\phi\sin\theta, \cos\phi) \quad \text{with} \quad \phi \approx 30.4^\circ$$

The measured radial velocity is, from the wind field $(u, v, w) = \boldsymbol{u} = \boldsymbol{u}(\boldsymbol{x})$

$$v_r(\theta) = \boldsymbol{n}(\theta)\cdot\boldsymbol{u}(d_f\boldsymbol{n}(\theta)) \quad \text{where} \quad h_f = d_f\cos\phi$$

[1] calculated the radial velocity variance as a function of the azimuthal position

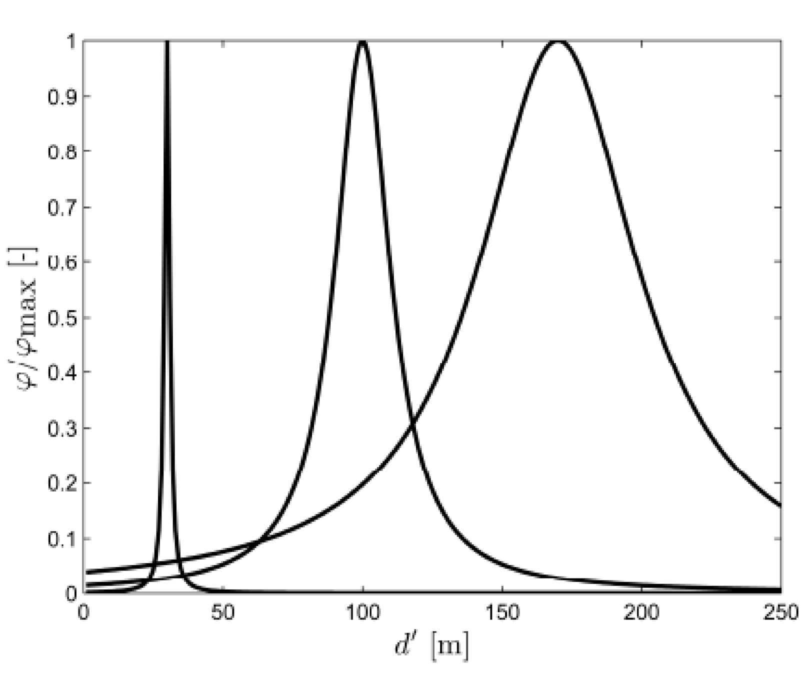
$$\sigma^2(v_r(\theta)) = \left\langle\left[\boldsymbol{n}(\theta)\cdot\boldsymbol{u}'(\boldsymbol{n}(\theta)d_f)\right]^2\right\rangle$$

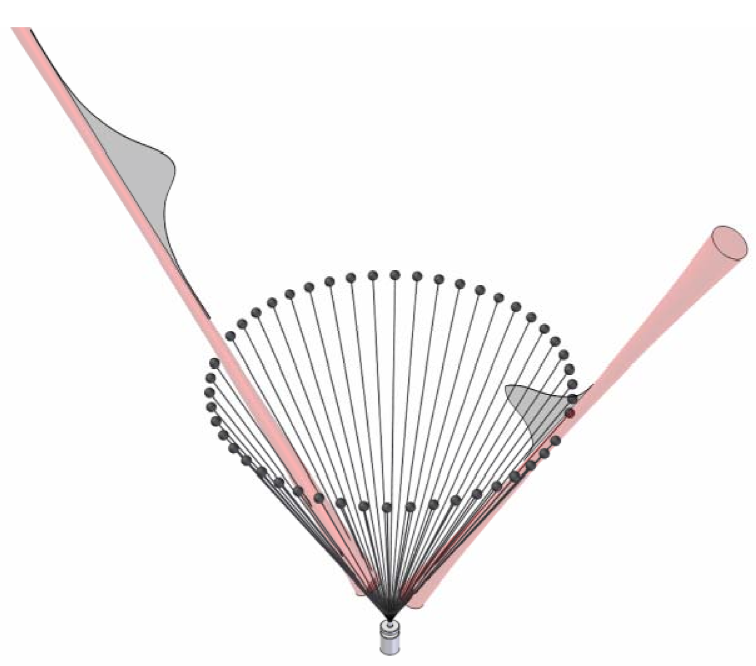
From which the momentum flux is proportional to the difference between the upstream and the downstream radial velocity variances

$$\langle u'w'\rangle = \frac{\sigma^2_{\text{down}} - \sigma^2_{\text{up}}}{4\sin\phi\cos\phi}$$

The attenuation can be estimated assuming

$$\tilde{v}_r(\boldsymbol{x}) = \int_{-\infty}^{\infty}\varphi(s)\boldsymbol{n}\cdot\boldsymbol{u}(s\boldsymbol{n}+\boldsymbol{x})ds = \int_{-\infty}^{\infty}\varphi(s)v_r(s)ds \quad \text{where} \quad \varphi(s) = \frac{1}{\pi}\frac{l}{l^2+s^2}$$

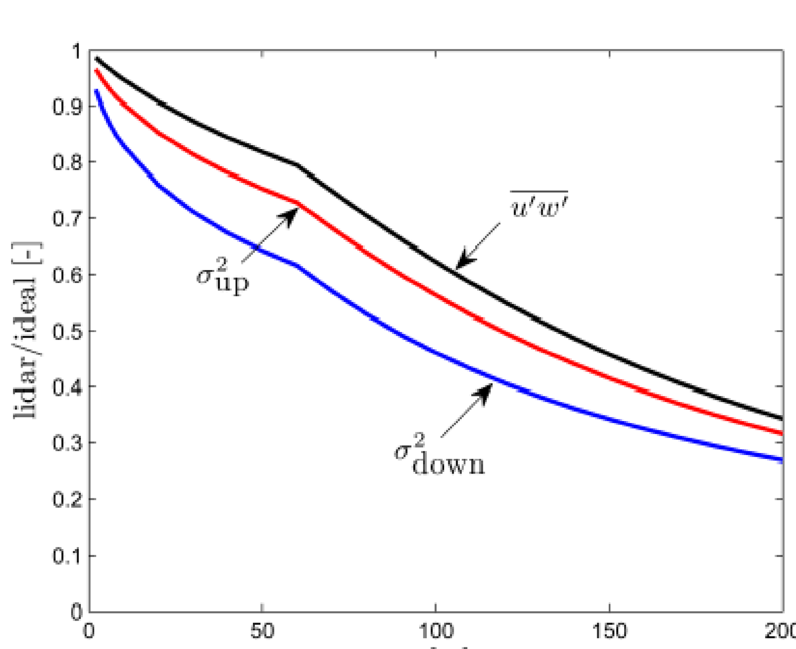




Thus, using the same normalization of the Fourier transforms as in [2]

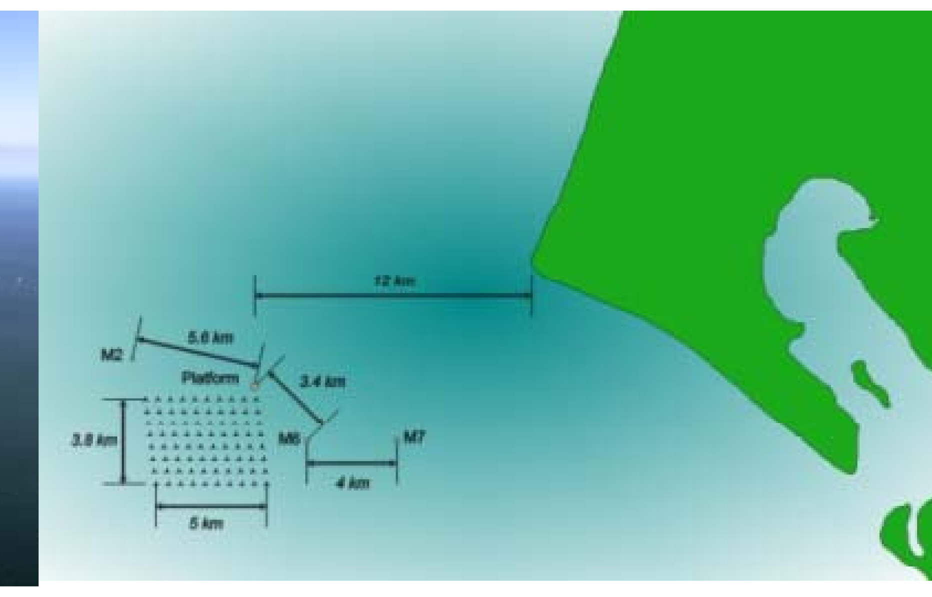
$$\sigma^2(\tilde{v}_r) = \int n_i n_j \Phi_{ij}(\boldsymbol{k})\exp(-2|\boldsymbol{k}\cdot\boldsymbol{n}|l)d\boldsymbol{k} \quad \text{where} \quad l = 2\text{ m}\times\left(\frac{d_f}{50\text{ m}}\right)^2$$

Choosing the turbulence length-scale profile in [3] and the spectral model in [2], the attenuation is accounted for:



The experiment

The ZephIR continous wave wind lidar was installed at the platform of the wind farm at 20 m AMSL. The platform is located 12 km from the west coast of Denmark. A met mast M2 was instrumented with Risø cups at 15 and 62 AMSL, a wind vane at 60 m AMSL and temperature sensors at 13 m AMSL and 4 m BMSL.

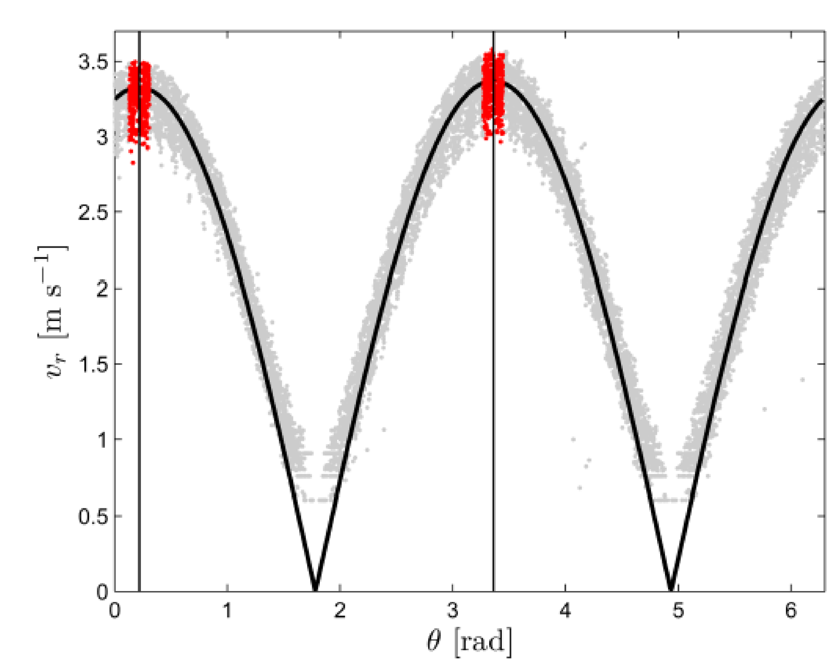


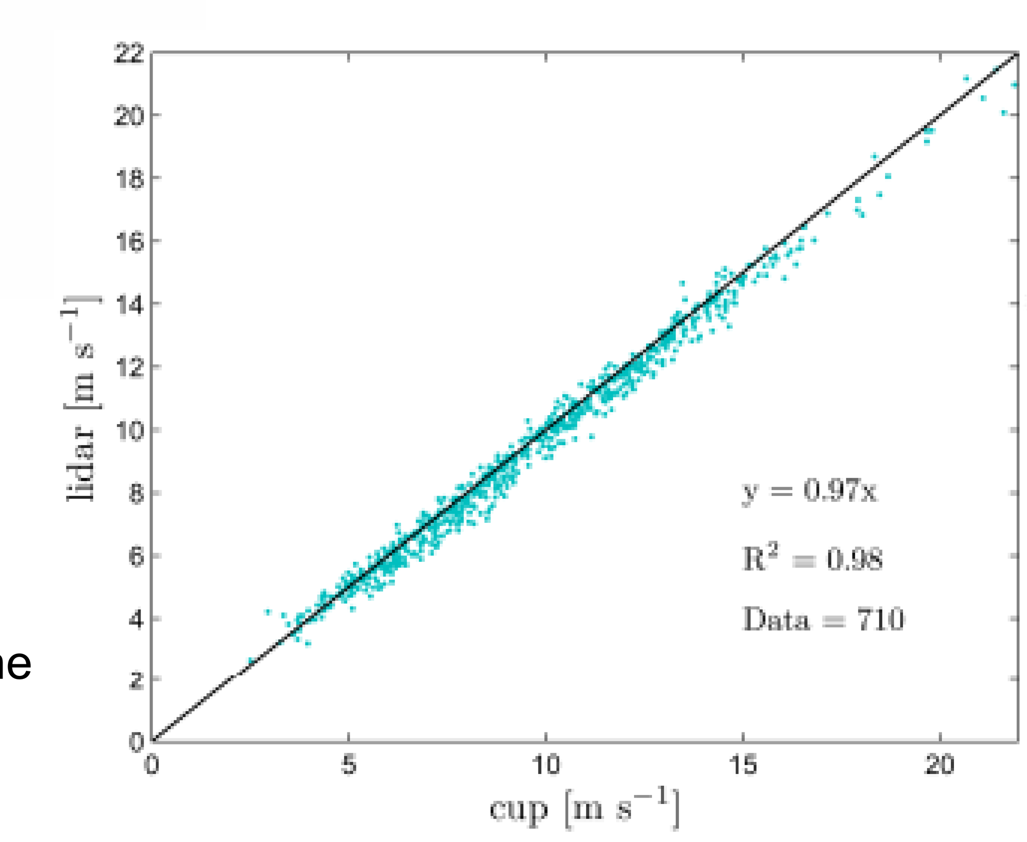
Results

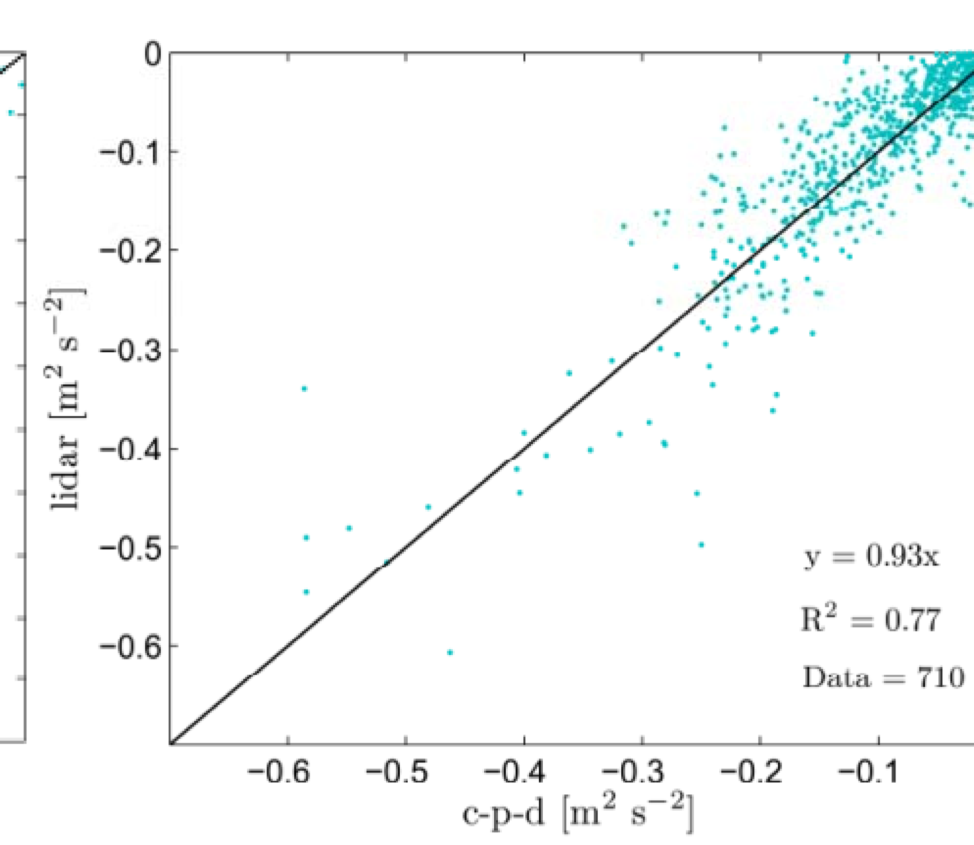
The momentum flux was estimated for near-neutral conditions from the cups as in [4]

$$u_* = \frac{\kappa U_{15}}{\ln\left(15\text{ m }g/\alpha_c u_*^2\right)} \quad \text{where} \quad -\langle u'w'\rangle = u_*^2$$

Using $\Delta\theta = \pm 5^\circ$ (as in the figure to the right), the results are shown in the figures below. To the left, the comparison of wind speed and to the right, the comparison of momentum flux. c-p-d is the momentum flux derived from the cups (Eqs above).







Conclusions

A method to measure the momentum flux from a continuous wave lidar is investigated. *Filtered* momentum flux observations can be directly extracted from the variance of the upstream and downstream radial velocities. They are in good agreement with the momentum flux derived from wind speed observations at the Horns Rev wind farm in the North Sea. The filtering effect can be predicted by using turbulence spatial statistics and accounting for the along-beam weighing function from the lidar.

References

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