Author’s Response

On the first referee comment on "Modelling the Spectral Shape of Continuous-Wave Lidar Measurements in a Turbulent Wind Tunnel" by Marijn Floris van Dooren et al., Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2021-233-RC1, 2021

26.11.2021

Marijn Floris van Dooren et al.

Dear Sir/Madam,

Thank you very much for taking the time to review our pre-print manuscript and for your helpful feedback and questions. We will rephrase your comments in blue and include our response in black.

Specific comments

L94: Provide some details about the seeding procedure (e.g., seed type, mean particle mass and volume, point(s) of application, any measurement about the concentration etc.).

We added the following description of the seeding procedure to the paper: ‘In order to maintain a sufficient number of aerosols in the wind tunnel to reflect the laser beam, seeding with Di-Ethyl-Hexyl-Sebacat (DEHS) was applied every few hours with a PALAS AGF 10.0 liquid nebulizer at the back of the wind tunnel, using the closed return wind tunnel itself for circulation. DEHS has a density of 0.91 g/cm^3 and a mean particle diameter of 0.5 µm. The aerosol concentration was not confirmed by measurement; however, the quality of the WindScanners' backscatter signal was used as an indirect indicator’.

L125: Provide a quantification of the time lag and, if possible, a plot reporting the mentioned cross-correlation.

We have quantified the time lag for the three cases shown in the paper (1a, 1b and 2c) and provided plots of the cross-correlation. The time lag includes the deviation in the clock time between the respective WindScanner and hot wire computers, but more importantly, illustrates the delay in activation of the hot wire logger after the WindScanners. We consequently started the WindScanner measurement first, and afterwards activated the hot wire measurement data logger for a duration of exactly 10 minutes. This procedure guaranteed that we consistently had full 10-minute data sets for both anemometers.

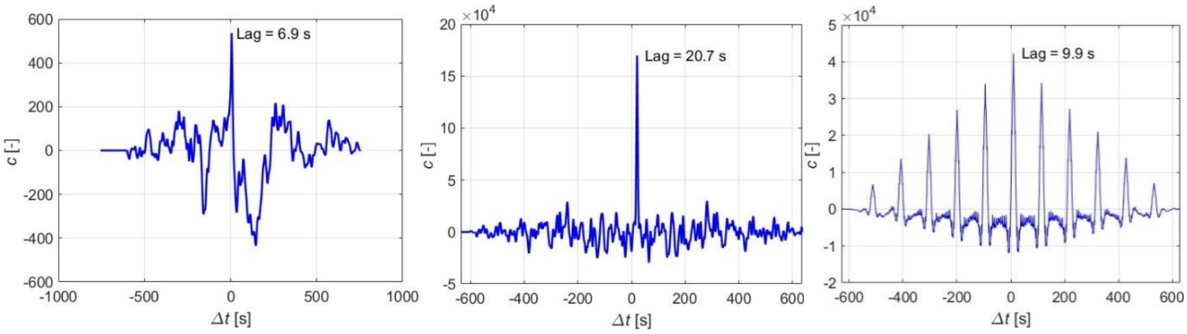

Figure 1: *Plots of the cross-correlation function between lidar and hot wire time series for three cases (1a, 1b and 2c), used for the temporal synchronisation*.

Please note that in all cases the time lag can be confirmed convincingly. Especially for the high turbulence case (1b) the cross-correlation function is unambiguous. For case 2c there are multiple high peaks because of the repetitive gust protocol, but the peak closest to $\Delta t = 0$ s is the relevant one.

Although the temporal synchronisation between the WindScanners and the hot wire are an important aspect of the data analysis, we regard this as a trivial procedure. Therefore, we would like to refrain from adding these plots to the paper itself.

L145: The equality between the Full Width at Half Maximum (FWHM) and probe length holds for a continuous wave-lidar, whereas for a pulsed lidar those are distinct parameters. Please specify them.

We are aware that the definitions for probe length and Full Width at Half Maximum length are different between cw-lidar and pulsed lidar technology. In order to avoid confusion, we would like to keep only the definitions for cw-lidar in the paper. However, it is explicitly mentioned, where applicable, that the definition is only valid for cw-lidar (e.g. **L143** and **L150** in the revised manuscript).

L163: It is more correct to state that their contributions, weighted by the respective sine and cosine functions, are negligible with respect to u_p.

Thank you for pointing out that it is more reasonable to assume that $\sin\chi\cos\delta\, v$ and $\sin\delta\, w$ are negligible with respect to u_p rather than assuming $v = 0$ and $w = 0$. We agree with this and have corrected this statement in the paper accordingly.

L212-213: Do you have any reference assessing this assumption? In any case, this procedure does not make much sense to me as, in case of lidar measurements, the noise is related to random fluctuations of the backscattered signal, which introduces an uncertainty in the Doppler shift (see e.g. Frehlich and Yadlowsky, 1994; Frehlich, 1997 for pulsed Doppler lidar). Hypothesizing a connection between the noise and physical properties of the turbulent flow is a strong statement that needs to be better justified. As validation, you can quantify the noise from the lidar data in an independent way, for instance the auto-correlation method of Lenshow *et al*. (2000).

We were not able to identify references that suggest a relationship between the lidar spectral noise level and flow parameters such as the energy dissipation rate and mean wind speed. However, we found very clear indications that such a connection does exist and would like to elaborate on it. First, we started with the assumption that the noise in a lidar measurement should be related to random fluctuations of the backscattered signal only, and that this is a property inherent to the lidar measurement principle and not to the physical properties of the turbulent flow. However, in our analysis we saw a convincing increase of the noise level for more energetic flows with higher wind speeds. We have evaluated various possible dependencies. The following lists the steps describing our empirical analysis of the lidar spectral noise estimate:

1. For each case (1a, 1b and 2a-2e) we manually tuned the lidar noise standard deviation σ_η to the model in Eq. (10) for the best possible match between modelled and measured lidar spectrum.
2. With a linear regression, we then tried to identify a parameter or a combination of parameters that could best match those tuned values for σ_η.
3. In the end the best fit was found for the square root of the product of energy dissipation rate ε and mean wind speed μ_u.
4. We tried to make the units match by including physical constants, of which the gravitational acceleration parameter seemed to be the best candidate. However, the second referee was

sceptical about the inclusion of this unrelated parameter, which made us decide to leave it out and accept a constant with a unit instead, indicating that there might still be unidentified parameters playing a role in the estimation of the lidar spectral noise level.

Figure 2 shows the relationship of σ_η with the mean wind speed μ_u and the standard deviation σ_u. The fit is not convincing, although the dimensions match.

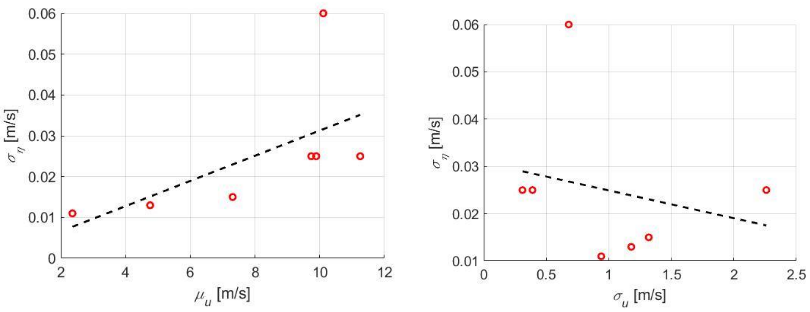

Figure 2: *Plots of the relationship of the lidar spectral noise standard deviation σ_η with the mean wind speed μ_u and the standard deviation σ_u, respectively*.

Figure 3 displays the relationship of σ_η with three different definitions of the coefficient of variance c_v, which is like the standard deviation σ_u, but only considers the small-scale fluctuations, which are most likely to influence the lidar noise. The three plots look similar, although the absolute values are different. The fit is a significant improvement compared to the standard deviation σ_u of the full time series. The unit matches to m/s.

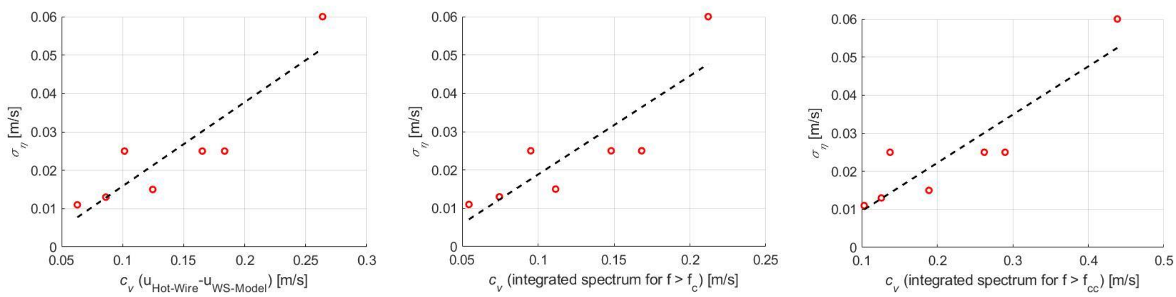

Figure 3: *Plots of the relationship of the lidar spectral noise standard deviation σ_η with the coefficient of variation c_v calculated in different ways; Left: Difference between the modelled lidar time series (only Lorentzian filter without added noise) and the hot-wire time series. Middle: Integrated coefficient of variance of the hot-wire spectrum from f_c to infinity. Right: Integrated coefficient of variance of the hot-wire spectrum from f_{cc} to infinity.*

Finally, Fig. 4 shows the more convincing relationships that include the energy dissipation rate ε (with the unit m^2/s^3), both alone and in combination with the mean wind speed μ_u.

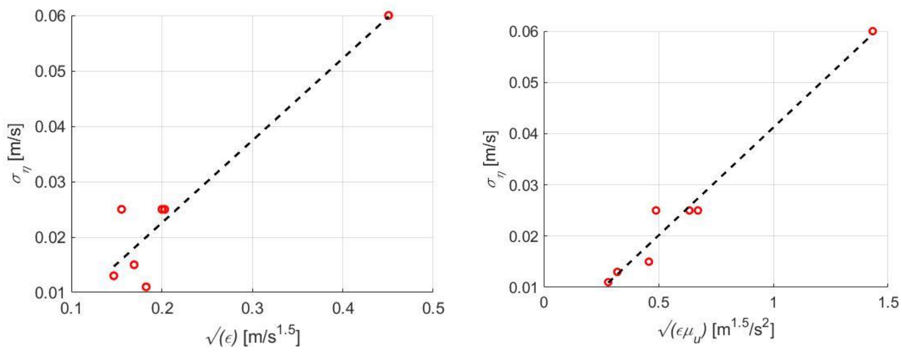

Figure 4: *Plots of the relationship of the lidar spectral noise standard deviation σ_η with the square root of the energy dissipation rate and the product of it with the mean wind speed, respectively*.

Based on this thorough empirical analysis, we decided that there is a convincing relationship between the noise standard deviation and the energy dissipation rate in combination with the mean wind speed of the flow. Our interpretation of this phenomenon is that more energetic flows, with a higher energy dissipation rate, inhabit more pronounced fluctuations and gradients in the probe volume of the cw-lidar, which result in a higher uncertainty in the estimated wind speed that influences the small-scale fluctuations in the cw-lidar time series, regardless of the Lorentzian low-pass filter effect.

This hypothesis needs more elaboration. Most likely the white noise is partly due to shot noise of the lidar, and partly related to global flow parameters. Please note that we are not suggesting the white noise is in any way correlated to the flow in the time domain, it is mainly the notion that global flow parameters could influence the absolute value of the lidar noise standard deviation. The model is not yet complete and might rely on further flow parameters, e.g. time and length scales, and lidar parameters.

Since we are convinced that this could be an interesting finding, we would like to keep the adjusted model described by Eq. (11) in the paper. Currently the empirical analysis is not included in the paper itself, but if this is deemed necessary, we will add (part of) this elaboration as an appendix.

L253: Showing a correlation between instantaneous values may be questionable as the latter are affected by the uncertainty due to the lidar noise (which has not been removed) and the interpolation of the hot-wire signal onto the lidar time stamp. If you want to compare the recorded time distributions, I recommend to at least perform a moving average of the signals and then apply the linear regression. As an alternative, you can calculate mean velocity and standard deviation over non-overlapping periods (whose length must be carefully established) and then compare them.

Instead of correlating instantaneous (and linearly interpolated) measurement values, we agree with your suggestion and performed a moving average before creating the correlation plots. We used a window of 20 samples, since this way the effective averaging of the 451.7 Hz time series will yield a smoothed time series where frequencies above ~22.6 Hz are filtered out. This value is just below the lowest cut-off frequency of the lidar measurement modelled by means of the Lorentzian filter full width half maximum among the three presented cases. The effect of the smoothing on the goodness of fit coefficient for the three cases portrayed in the paper is listed in Table 1.

Table 1: *Improvement of the goodness of fit coefficient for the correlation between the smoothed WindScanner 2 and hot wire time series for three cases (1a, 1b and 2c).*

Case	Figure	R^2 (instantaneous)	R^2 (smoothed)
1a	9	0.656	0.790
1b	10	0.931	0.957

2c	16	0.950	0.975

The moving average procedure mostly benefits the goodness of fit coefficient for case 1a, while also slightly increasing the already high values of cases 1b and 2c.

L319: As for Figures 9 and 10, I recommend to compare either a moving average over a short time period.

See the answer above for **L253**.

Technical corrections

L2: Add the meaning of the acronym "lidar".

We included the meaning of the abbreviation 'lidar' (light detection and ranging) for the first occurrence in the paper.

L4-6: Please consider to change the statement to: "The hot-wire anemometer is used as theoretical reference to assess the lidar-based statistics, time series and spectra". Remove the mention to the Taylor hypothesis as the spectra are evaluated in frequency.

We changed the statement to your proposed alternative. We would still like to mention the 'theoretical spectrum using Taylor's Hypothesis', since the latter is a vital assumption to convert the spectral model, which uses the spatial Lorentzian filter as a basis, from the wave domain to the frequency domain.

L22: Please add some references to important wind tunnel studies of wind turbines.

We included three additional references related to wind turbine tests in wind tunnels (Campagnolo *et al.*, 2016; Tian *et al.*, 2018; Berger *et al.*, 2021). Another relevant paper (Bottasso *et al.*, 2014) was already mentioned in the same paragraph.

L32: Please state that, in contrast to the probing techniques mentioned in the previous paragraph, the lidar technology has been originally developed for real-scale studies and you are proposing a novel implementation of this technology.

We included the sentence 'In contrast to the other aforementioned sensors, lidar technology was originally developed for real-scale studies.', right before lidar measurements in wind tunnels are mentioned (**L35**). We also changed the word 'new' to 'novel' (**L36**).

L34: Replace "[…] but make up for it […]" with "[…] but, on the other hand, […]".

We changed the sentence to 'Lidars measure… …aforementioned sensors, but are, on the other hand, a… …measurement technique'.

L55: Please add a short paragraph to describe the content of the next Sections.

The structure of the paper is now announced at the end of the introduction.

L71-74: Replace "However, for the measurement campaign described in this paper, they are placed near the walls of the wind tunnel. Three of them can be seen on the right side of the nozzle in Fig. 1. The two remaining ones are parked at the back of the wind tunnel and serve as measurement platforms for the lidars, as illustrated by Fig. 2" with: "For the present campaign, only two test sections are used as measurement platforms for the lidars, as illustrated by Fig. 2."

We rewrote this sentence, in a slightly different way than how you proposed, to 'For the present campaign, all test sections are placed near the walls of the wind tunnel, and two of them are used as measurement platforms for the lidars…'.

L78: Specify that two identical continuous-wave lidars are used in this campaign.

The first sentence of this paragraph now states that both lidars are identical.

L81: Specify that the Doppler shift is calculated with respect to the emitted laser frequency.

We added the following sentence: '…Doppler shift in Hertz. The latter is defined as the difference between the backscattered and emitted laser frequency'.

L135: Add reference to Sjöholm *et al*. (2009).

The reference to Sjöholm *et al*. (2009), which was already part of the bibliography, is now included in this line.

L187: I think here you are referring to Eq. (7). If so, please correct.

We were indeed referring to Eq. (7) and not Eq. (6), so we corrected this reference accordingly.

L219: Please add: "The Kolmogorov spectrum in the inertial subrange is modelled as follows: […]".

We now properly introduced Eq. (12) and relocated the reference to the last sentence: 'The Komolgorov spectrum in the inertial sub-range is modelled by Eq. (12): […]'.

L226: Specify that, at this stage, the comparison is done in time between instantaneous values.

It is now stated that the comparison applies to instantaneous values, as such: '…was carried out for instantaneously sampled time series on a 10-minute basis…'.

L243: Please add that this difference will be addressed in the following part of the Subsection.

We added the sentence 'This difference will be addressed in the following part of the Subsection'.

L350: It is incorrect to state that the low-frequency peaks do not have physical significance. I would change this sentence with "As they result from external gust variations, these peaks are not deemed to be due to turbulence […]".

We agree that it is incorrect to label the frequency peaks as 'no physical significance'. The second referee also pointed this out. We meant that they are not associated with atmospheric turbulence, but that does not mean it is not a physical phenomenon. We gladly accept to use your alternative wording.

L358: For the sake of clarity, please report the definition of coherence here.

A precise definition of the coherence, including an equation, is added to the paragraph.

L386: To my understanding, here you are applying the Lorentzian model described in Sect. 3.2 to the hot-wire spectrum and qualitatively compare the similarity with the WindScanner 2 streamwise spectrum. Please state this clearly at the beginning of the Subsection.

Your understanding of the implementation of the model and its evaluation is correct. We have added the sentence 'The modelled lidar spectrum is generated by applying the methodology on the measured hot-wire spectrum.' (**L402-403** of the revised paper) to emphasise it more clearly.

References

Berger, F., Onnen, D., Schepers, J. G., and Kühn, M.: Experimental Analysis of Radially Resolved Dynamic Inflow Effects due to Pitch Steps, Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2021-70, in review, 2021.

Bottasso, C. L., Campagnolo, F., and Petrović, V.: Wind Tunnel Testing of Scaled Wind Turbine Models: Beyond Aerodynamics, Journal of Wind Engineering and Industrial Aerodynamics, 127, 11–28, https://doi.org/10.1016/j.jweia.2014.01.009, 2014.

Campagnolo, F., Petrović, V., Schreiber, J., Nanos, E. M., Croce, A., and Bottasso, C. L.: Wind Tunnel Testing of a Closed-Loop Wake Deflection Controller for Wind Farm Power Maximization, Journal of Physics: Conference Series, 753, https://doi.org/10.1088/1742-6596/753/3/032006, 2016.

Frehlich, R. G., and M. J. Yadlowsky.: Performance of mean-frequency estimators for Doppler radar and lidar, Journal of atmospheric and oceanic technology 11.5, 1217-1230, 1994.

Frehlich, R. G.: Effects of wind turbulence on coherent Doppler lidar performance. Journal of Atmospheric and Oceanic Technology 14.1, 54-75, 1997.

Lenschow, D. H., Volker W., and Christoph S.: Measuring second-through fourth-order moments in noisy data. Journal of Atmospheric and Oceanic technology 17.10, 1330-1347, 2000.

Sjöholm, M., Mikkelsen, T., Mann, J., Enevoldsen, K., & Courtney, M.: Spatial averaging-effects on turbulence measured by a continuous-wave coherent lidar. Meteorologische Zeitschrift, 18(3), 281-287, 2009.

Tian, W., Ozbay, A., and Hu, H.: A Wind Tunnel Study of Wind Loads on a Model Wind Turbine in Atmospheric Boundary Layer Winds, Journal of Fluids and Structures, 85, 17–26, https://doi.org/10.1016/j.jfluidstructs.2018.12.003, 2018.