Response to referee 2

Dear referee,

Thank you for your general comments on our work, which we consider very important in helping us to improve the manuscript. Here is our response to each of your comments. Comments from the reviewer are reported in black and followed by our answers in blue.

Best regards,
The authors

Main comments:

(1). Probe Volume in simulations: It makes a lot of sense to me that in 4.1 and 4.2 the measurement volume is not considered, since the analysis with the measurement also uses the "unfiltered" radial velocities. Of course, the method from 3.1 could be also applied to simulated data, but this would add more complexity to the simulation and paper. However, in 4.3, volume averaging is applied. This then causes issues with the bias (first paragraph of Section 5) and also is a bit inconsistent. Therefore, I would propose the authors to consider following ideas (or any other which could solve the issue):

a) Add some lines in the discussion and in the beginning of Section 4 about that issue.

b) Apply the method from 3.1 also to the simulated measurements (if possible) from Section 4.3.

c) Ignore volume averaging in Section 4.3 as well, focus only on cw lidar.

For idea a and b, Section 4.3 could be renamed to "… lidar opening angle, focus distances, and lidar type". For idea c, you would need to remove the "lidar type dependency investigation" from the abstract etc. Personally, I tend to Option c, if not too much work, since the paper already provides a lot of information and the lidar type dependency investigation is maybe not so interesting as the rest.

For Fig. 13 in the revised manuscript (Fig.12 in the preprint), we were doing option (b) to simulate and process lidar measurements in a way that is close to the one we applied to field measurements. The CW lidar probe volume was simulated and then the probe volume averaging effect was compensated by applying the method from Section 3, as mentioned in the caption of Fig. 13.

For Fig. 14 (Fig.13 in the preprint), we decided to do option (a). As explained at the beginning of Section 4, "Results in Sections 4.1 and 4.2 neglect the lidars' probe volumes to study the influence of the number of beams. Nevertheless, for CW lidar systems, the probe volume increases with the square of the focus distance. Also, for pulsed lidar systems, the probe volume effect cannot be easily compensated since the Doppler spectra are usually not accessible. Therefore, the probe volumes are considered in Section 4.3 to show how different factors are altogether influencing the turbulence estimations."

The positive bias of v and w variances estimations using a 6-beam lidar with 15 deg in Fig. 13 (revised manuscript) is slightly larger than those in Fig. 10, because the simulated radial velocity variances are different with and without considering the probe volume. As explained at the beginning of Section 5, the

biases are due to the small coefficients for R_{vv} and R_{ww} if the half-cone opening angle is small, and the matrix on the left side of Eq. (15) is ill-posed. The biases are overall consistent in the two figures.

(2). The discussion section could be improved: The impact on the matrix from Equation 15 on the opening angle could be discussed in more detail. This might also help to give a more precise conclusion e.g. in the abstract, only a "large opening angle" is mentioned, but there should be an optimum, since e.g. for very large angles closer to 90 deg, the uncertainty for the u component should increase a lot. The first paragraph is also focusing on Figure 12 only and some discussion on the results from Section 4.1 and 4.2 could be added. Further, the second paragraph mentions the assumed frozen turbulence and homogeneity as well as the induction zone. Here a discussion of the impact of these effects could be added. The impact of other assumption/limitation of this study could be added, e.g. the limitation to small yaw misalignment angles.

As we added in the discussion "As shown in Fig. 13, increasing the lidar opening angle improves the accuracy and uncertainty of R_{vv} and R_{ww} estimations. The uncertainty of σ_u^2 is not much influenced if the lidar has a central beam that always aligns with the mean wind, e.g. the six-, 51-beam lidars, and the SpinnerLidar. For nacelle lidars without a central beam, enlarging the opening angle brings higher uncertainty to σ_u^2 estimation, which is a key parameter for assessing wind turbine load. Therefore, the optimum opening angle for turbulence estimations depends on which Reynolds stress is of interest. In addition, for control applications, the large opening angle is beneficial for measuring wind directions, but sacrifices the accuracy of rotor-effective wind speed and wind shear estimations. The optimum opening angle is also very much relevant to the turbine's size.", and in conclusion "The optimum value of the opening angle depends on the Reynolds stress term of interest and also the wind turbines' size. Further studies or experiments are needed to study the best opening angle of the 6-beam lidar for different applications.".

We added some text to highlight the significance of the results in Sections 4.1 and 4.2.

We added some text in the discussion: "Taylor's frozen turbulence hypothesis (and homogeneity) is assumed throughout our numerical simulations, because the wind evolution is not very relevant to turbulence statistics, more to the rotor-effective wind speed estimations (Chen et al., 2021). Mann et al. (2018) showed that turbulence is slightly affected by the stagnation in front of the wind turbine rotor as it goes through the induction zone. The change of the low-frequency wind variation is related to the thrust coefficient of the wind turbine, but the main turbulence statistics do not change. In addition, the yaw misalignment of the wind turbine is not considered in this work. A small yaw misalignment (below 20°) does not affect much σ_u^2 estimations but increases the uncertainty of R_{vv} and R_{ww} estimations. For modern wind turbines with very large rotor disks, the single-point turbulence statistics are not a good representative of the inflow turbulence affecting the wind turbine. The least-square procedure cannot be used to characterize the inhomogeneous inflow. New methodologies, e.g., constrained simulations (Dimitrov and Natarajan, 2017;Conti et al., 2021), are needed to reconstruct the inhomogeneous wind field."

<u>Specific comments on some minor details:</u>

(1). l82: you could introduce U.

In the revised manuscript, we introduced U in L84.

(2). 2.: A simple sketch for the angles would be helpful. You could also explain the coordinate system, which might be helpful to understand, why e.g. the opening angle is between the beam and the NEGATIVE x-axis.

We added a sketch showing the definition of the coordinate system and the beam angles for nacelle lidar modelling, see Fig. 1 in the revised manuscript. The opening angle is between the beam and the negative x-axis in a downwind view, since the x-axis is along the mean wind direction and the beam is pointing towards the inflow.

(3). Figure 2, 3, 6: the z label ("z [m]") is mirrored.

Thanks for noticing that. We corrected the z label.

(4). Equation 6: The error function usually uses \sqrt(\pi) in the denominator instead of \pi. And you could also mention that Erf is the error function.

Yes, you are right. We corrected it. Thanks for noticing the typo.

(5). L112: "frequencies … inside the volume are not considered except the dominant frequency detected by the centroid method": this is a bit inaccurate, since the range weighting function acts as a filter and damps high frequencies in the wind much more than lower frequencies, but is not perfect (i.e. considering only some frequencies).

We agree. The sentence is changed to "Variances calculated from the centroid-derived radial velocities are attenuated by the lidar probe volume, which acts like a low-pass filter to the wind velocity fluctuations." In L115.

(6). Equation (13): The partial derivative from Equation (12) "(…) ^2" should be "2*(…)*n_i*n_j". Maybe I miss something. But if not, you could add the 2. It does not make any difference, Equation (13) is correct without it, but it might be easier to reproduce.

You are right. We added the 2 to Eq. (13) in the revised manuscript.

(7). Equation (14) and (15): Similar to the previous comment, couldn't you simplify these equations by removing n_i and n_j, which is present on both sides? This would help with the discussion on the impact of this matrix. But maybe I totally misunderstood the complexity.

No, we cannot cancel the $n_{i,j}$ that are present on both sides, because e.g. $\Sigma n_1 \sigma_{vr}^2$ is different as $n_1 \Sigma \sigma_{vr}^2$. The n_1 can be removed if they are the same for all beams, i.e., if the opening angles of all beams are identical.

(8). l155: is a simple mean over all radial velocity components already providing already the variance in u, v, and w? There should be still some weighting with the cos^2, right? If so, this might be a bit misleading.

Assuming turbulence is isotropic, i.e., $R_{uu} = R_{vv} = R_{ww} > 0$ and $R_{uv} = R_{uw} = R_{vw} = 0$, Eq. (15) can be written as $(\Sigma n_1^4 + \Sigma n_1^2 n_2^2 + \Sigma n_1^2 n_3^2) R_{uu} = \Sigma n_1^2 \sigma_{vr}^2$. If the lidar has only one opening angle, n_1 of all

beams are identical, the equation can be further simplified to $\Sigma(n_1^2+n_2^2+n_3^2)R_{uu}=\Sigma\sigma_{vr}^2$. From Eq.(3) we know that $n_1^2+n_2^2+n_3^2=1$, so $R_{uu}=\frac{\Sigma\sigma_{vr}^2}{N}$, where N is the number of beams.

(9). Section 3.3: The scan rate of the lidar systems is not mentioned here. Did you use the time resolution of the wind field or did you use a certain scan rate (e.g. 200 Hz for the SpinnerLidar or 4 Hz for a typical pulsed lidar)?

In the revised manuscript, we explained at the end of Section 3.3 that "The time lag between each measurement within a full scan is not considered but assumed that measurements are taken at the same time. In the numerical simulations neglecting lidar probe volume (see results in Sect. 4.1 and 4.2), the time resolution of the wind field is used as the lidar scan rate, i.e., lidars complete one full scan in dt = dx/U = 0.22 s. While in the simulations considering lidar probe volume (see results in Sect. 4.3), the lidars are assumed to finish a full scan in 2 s."

(10). L183: here it is not clear to me, what do you mean with velocity bin. One would expect a discretization of the distance from -M to M. Also, the "bin^{-1}" for the unit of the resolution might not be necessary, since I think it is clear that the resolution is per bin.

The Doppler radial velocity spectrum is a function of v_r, which is discretized into many bins. We changed the sentence to "The resolution of Doppler radial velocity spectrum is 0.1 m/s per velocity bin." in Section 3.3.

(11). Table 1: the typical CW lidar has a beam radius of 28 mm, which would be 2.8 x 10^-2 m, not -4. I assume this is a typo, since for the 2.44 m mentioned in Section 3.4 one need 28 mm and 0.28 mm would be very small.

*You are right. We corrected the typo to 2.8*10^{-2} m. Thanks for noticing it.*

<u>Specific comments on some very minor details:</u>

(1). Table 1 and 2: I am not sure about the WES style, but in general it is a bit more common to use the caption on top rather below the table. Please check.

We think this is the WES style in preprint. According to our experience, the captions will be on the top of the table in the final published version.

(2). Figure 7, caption: you could avoid the line break between "62" and its unit "m", e.g., using the latex package siunitx.

We corrected it in the revised manuscript.

(3). l77: "Section 5" might be more consistent compared to "Sect. 5."

We corrected it in the revised manuscript.

(4.) When you have a list of numbers, e.g. l173 or l186, you could use white spaces after the comma.

We corrected it in the revised manuscript.

References:

Chen, Y., Schlipf, D., and Cheng, P. W.: Parameterization of wind evolution using lidar, Wind Energy Science, 6, 61–91, https://doi.org/10.5194/wes-6-61-2021, 2021.

Conti, D., Pettas, V., Dimitrov, N., and Peña, A.:Wind turbine load validation in wakes using wind field reconstruction techniques and nacelle lidar wind retrievals, Wind Energy Science, 6, 841–866, https://doi.org/10.5194/wes-6-841-2021, 2021.

Dimitrov, N. and Natarajan, A.: Application of simulated lidar scanning patterns to constrained Gaussian turbulence fields for load validation, Wind Energy, 20, 79–95, https://doi.org/10.1002/we.1992, 2017.