Review of the article

"Advancing airborne Doppler lidar wind profiling in turbulent boundary layer flow - an LES-based optimization of traditional scanning-beam versus novel fixed-beam measurement systems "

Review Summary

submitted by Gasch et al.

(AMT)

LES simulations are used to compare the performance of airborne Doppler wind lidar measurements with conventional scanning techniques and a multiple fixed-beam approach for probing planetary boundary layer (PBL) winds. The paper is well written and clearly demonstrates a few of the advantages that a fixed-beam system would have especially regarding the reduction of the representativeness error in a turbulent wind field which is particularly interesting as such a fixed- beam approach is easily implementable with novel all-fiber-based laser transmitters. Hence, it is recommended to accept the paper manuscript after addressing the points that are raised below.

We would like to thank Dr. Witschas for the time and effort taken in reviewing the manuscript. The discussion of the points raised below certainly improves the quality of our study. We have adapted the manuscript based on the answers given below, also taking into consideration the points raised by the reviewer Dr. Emmitt. We hope that the manuscript is acceptable for both reviewers in the revised form.

General comments

- The main rationale of the paper manuscript is to compare the wind results retrieved from a fixed-beam approach (1 beam nadir, 4 beams off-nadir) with the one obtained from a scanning approach (continuous scanning with a 20°/s scanner rotation speed). However, a more suitable comparison to a scanning approach would actually be to consider a step-and- stare scanning with 5 LOS measurements (1 nadir and 4 off-nadir) comparable to the one provided by the fixed-beam approach. Considering 1-s for each of the LOS measurements, such a system would provide wind data for all 5 seconds with similar LOS information as available from the fixed-beam measurements, however, with a temporal discrepancy. Similar scanning schemes are already applied to airborne wind lidar systems. Thus, it would be recommended to replace or update the current analysis with such a scanning scheme. This would also further confirm and strengthen the benefit of using a fixed-beam approach for current wind lidar systems.

Answer: Our study aims to quantify the advantage of the novel-fixed beam design compared to **traditional ADL systems** available **for PBL research** up to date, as stated in the title of the study. For this reason, we used the scanning system with comparable settings as those used by Gasch et al., 2020.

To provide more context on used scan pattern to the reader, we have now included a literature overview on reported scan techniques and an extended discussion. In addition, based on this review and taking into consideration the comments made by the reviewer Dr. Emmitt, we have now switched from the continuous scan pattern to a step-and-stare (SNS) pattern with a much faster scanner. The new SNS pattern is based on scan pattern which have been reported in PBL literature before (also see answers in Dr. Emmitt's review). To enable a better comparison, we have added an additional vertical stare to the twelve-point SNS pattern as suggested in the above comment. Thus, we now use an overall thirteen-point SNS pattern (SNS13) with a rapid scanner as a reference system.

We are unaware of a system with a very rapid 5 s SNS scan (SNS5), as proposed in your comment, having been used for wind profiling on slow and low flying aircraft for PBL research up to date. Since it hasn't been used in PBL research up to date, we consider the fast SNS technique mentioned by Dr. Witschas to be another promising approach, which may be possible to build in the future. One possible solution appears the use of double-wedge scanners (as used by Dr. Witschas on fast jet aircraft), although double-wedge scanners may be limited in their ability to scan at shallow elevation angles (an important driver of retrieval error).

For your reference, we have also simulated the SNS5 pattern and attach the results to this reply. While wind profiling quality and availability is slightly better than for the SNS13 pattern, the retrieval availability and accuracy still show reduced quality compared to the FIX5 system. Especially at short averaging distances < 450 m the profile availability is strongly reduced. The reduction in error levels for some background wind speeds at very short averaging distances is due to the CN_{max} = 10 quality filtering, which leaves very few but well sampled retrieval volumes. In addition to the retrieval resolution loss, an increase in error levels is observed for both wind components if steeper scan elevation angles are used. Additionally, quality filtering with CN_{max} = 10 results in a loss of wind profile points at the steepest elevation (80 degree) compared to the SNS13 pattern. Overall, having the highest resolution and lowest error possible is crucial for PBL studies in order to resolve the spectrum of turbulence down to the inertial subrange. Hence, we believe that the improved wind profiling capabilities of the novel fixed-beam approach are needed.

Overall, our study does not claim to be exhaustive and investigate all possible improvement options. We believe the fixed-beam technology provides unique advantages and is an important step forward, which is why we are building and investigating such systems. There is also potential merit of the very fast SNS pattern, but we believe that this merit needs to be carefully examined in a future study. Some of the pros and cons go beyond the LES-based wind profiling accuracy analysis and require in-depth discussion, which is beyond the scope of this study and would extend beyond the minor changes suggested:

- A fixed-beam system enables a simplification of the rack design as no moving parts are needed. This simple design is beneficial for system design, certification and reliability and may enable easier transfer of the Doppler lidar technology between different carrier aircraft.
- No measurement time is lost due to slewing for fixed-beam systems.
- It is important to have uninterrupted vertical wind measurements inside the PBL at high resolution to include and resolve the inertial subrange in the measurements. Uninterrupted vertical wind measurements, yielding highest spatial resolution, are only available from a fixed-beam system.
- Since the inertial subrange is resolved it may be possible to retrieve turbulence using a fixed-beam system. We investigate the possibility to retrieve turbulence using the fixed-beam system in an upcoming study (Kasic et al., in preparation).
- For a SNS system, the additional design, manufacturing and certification of a scanner unit is necessary, which is expensive. As an advantage, only a single lidar unit is needed in a SNS system, which can therefore potentially use more expensive technology enabling higher lidar radial velocity measurement quality. However, the lidar beam is attenuated by the scanner, reducing the benefit of the more expensive lidar unit. The fiber-based lidar units to be used in the fixed-beam system offer sufficient measurement quality for PBL turbulence measurements where sufficient return signal is available. Hence, the need for using more expensive lidar units is marginal. Additionally, the fixed-beam directions offer the advantage of situation (aerosol return) dependent averaging times.

- A multiple fixed-beam system can still measure if one of the individual lidar units fail, whereas a single lidar and single scanner present single points of failure.
- A SNS system may allow for correction of the aircraft crabbing angle for improved curtain retrievals. However, correcting the crabbing angle will not solve issues caused by wind advection between measurements conducted at different times on the curtain below the aircraft (see our answer to the next question).
- A very fast scanner makes careful investigation of the pointing angle accuracy necessary. This issue is not considered in our current idealized simulation since beam pointing angle accuracy is stable for rigid fixed-beam systems.
- To our knowledge, double-wedge scanners offer limited possibilities for shallow scan angles, which is an important parameter for wind profiling quality, as shown by our results.

Based on the reasoning detailed above we have thus decided to compare the FIX5 approach with the traditional SNS13 approach in this study.

Changes in the manuscript:

Based on the above explanations we have adapted the manuscript to acknowledge the point and perspective presented by both reviewers:

- Based on the literature overview and comments by Dr. Emmitt we have adapted the reference scan pattern to the fast SNS13 commonly used for wind profiling in the PBL before.
- We now state that an even faster SNS approach also offers interesting potential and is worth investigating in the future (introduction, scanning section and conclusions).

- Somehow related to this issue: In chapter 4, you investigate the error dependency of the elevation angle and the number of fixed LOS beams. Would a similar optimization procedure also be possible for a (step-and-stare) scanning approach? Probably, also scanning schemes could be optimized for the respective situation and would for instance easily allow correcting for crabbing/crosswind.

Answer: Yes, the system setup optimization and error characterization are also possible for a SNS approach. Having switched to the SNS pattern in the manuscript we do so now for the beam elevation angle. While using a SNS approach would allow to correct for the aircraft crabbing angle (e.g. better aligning the forward and aft measurements on the ground track below the aircraft), it would still not be able to avoid effects caused by advection due to the time elapsed between the measurements. Advection effects depend on the speed and direction of the wind, which is also a function of altitude, in relation to the flight direction. The combination of both is complicated to consider, as they can both act in favor or against better alignment of the measurements. Already relatively small advection distances O(100 m) can cause noticeable retrieval error, since the integral scale of turbulence in the PBL is small. Additionally, as mentioned in the discussion above, pointing accuracy issues would have to be considered in more details for a fast SNS pattern.

Changes in the manuscript:

- We now mention the scanning-beam optimization as an interesting future point of study.

- As airborne wind lidars are also often used to probe the entire troposphere, it would be very useful to comment on the performance of a fixed-beam instrument in such a case. Probably there is no need to perform advanced LES simulations for that. But could you at least comment on the wind measurement performance in non-turbulent flow as it is expected in the free troposphere?

Answer: We expect that a fixed-beam system also offers advantages above the PBL. While retrieval error due to turbulence become less important above the PBL (but can still be considerable, see Weissmann et al., 2005), signal availability becomes increasingly important. In the free troposphere less scatterers are available, decreasing the signal to noise ratio. For this reason, longer accumulation times are needed to obtain useful radial velocities (more spectral averaging), which is also a main motivation for using SNS scanning approaches instead of a continuously scanning beam. This explains the expected benefit of the fixed-beam approach: Since all radial velocities are available continuously and with a stable aircraft speed projection, the needed averaging times to obtain a useful signal can be chosen individually for each beam, depending on the aerosol return available. In addition, no measurement time is lost due to the slewing of the scanner. Last, the continuous availability of the nadir beam for uninterrupted high resolution vertical wind measurements is expected to be beneficial for many application scenarios.

The LES-based simulator presented here does not include a simulation of the backscattering process and spectral analysis, therefore it cannot be used to assess the benefits of a fixed-beam approach on signal quality above the PBL. We hope to be able to provide more answers once the first measurements with the real system have been conducted, since the results depend on the signal quality of the fiber-based lidars.

Changes in the manuscript:

- We state that the simulation does not include a simulation of the backscattering process, hence we would like to not comment on free troposphere behavior as it is beyond the scope of this study.

- It is appreciated and understood that LES simulations provide a lot of advantages for system optimization. Anyway, wouldn't it be useful to directly compare the performance of a fixed-beam and a scanning system e.g. by ground measurements? Such a comparison would give further insights into the different approaches even without knowing the actual wind field truth. Although it is clear that such kind of measurements does not have to be included in this paper, it should be stated that such kind of measurements are foreseen to be performed in the future.

Answer: Real-world validation is certainly key besides the LES-based simulation. We do not see these two aspects as mutually exclusive but as inclusive instead. The LES-based simulations allow us to study system setup and retrieval strategy optimization before building and flying a real-world system. Since system design, manufacturing and flight test are expensive, this is desirable. Of course, any real-world system also needs to be validated with other measurement systems (e.g. ground-based, dropsondes, other aircraft), since they can suffer from a variety of other error sources not considered in the idealized LES-based simulation. An important example is the motion correction error (linked to beam pointing-angle calibration). Fortunately, real-world measurements also offer further validation diagnostics such as the lidar measured ground-return velocity. For this reason, extensive real-world validation of ADL systems have been performed in the past, and this will also be key for the fixed-beam systems under development. However, we believe flying and validating a whole range of elevation angles with a sufficient statistical basis is unfeasible due to the prohibitive cost. Hence, the ADLS optimization has been conducted.

Changes in the manuscript:

- Included statement on the need of real-world validation in conclusions.

General comments

- Page 2, line 37: O(10 km): Actually, this is constrained by the "old" scanner motors that are used. With an optimized system, horizontal resolutions of e.g. 4 km are feasible. Furthermore, this option is using 21 LOS! if 5 LOS would be used, the horizontal resolution would be ~1 km. This should be put into context here.

  We deemed this a rather recent study, therefore included it in this way. Reworded and added a very recent reference now, although only partial wind components are retrieved by the faster scan pattern and it has not been applied to PBL wind profiling so far. Also included a literature review now, see above comments.

- Page 2, line 54: five independent lidar systems: Probably, you are talking about beams or LOS directions, right?

  Yes, clarified now.

- Page 2, line 55: What is actually the vertical resolution of the lidar measurements (pulse length) that you are considering? 30 m? Do you use similar assumptions for the fixed-beam and scanning system?

  Yes, the vertical resolution is 30 m, corresponding to an expected (selectable) pulse length of 160 ns for the fixed-beam lidar systems. The 30 m resolution is equal for the fixed-beam and scanning system in our study. Since this is a rather technical information we would like to not discuss it in the introduction, we have now added this information in Tab. 2.

- Page 3, line 83: retrieval error introduced by turbulence: It would be nice to read the number that you get (quantitatively)...how large can this error get, and how large is it typically.

  The retrieval error very much depends on scan settings used and turbulent conditions present. We added a statement now to specify the order of magnitude.

- Page 4, line 98: question→questions

  Changed, thank you.

- Page 4, line 108: higher surface sensible heat flux: Is it still a realistic number or is it significantly higher than in the real world?

  This is a rather common surface sensible heat flux for a daytime continental convective PBL, now mentioned.

- Page 8, lines 173 ff: Rotation speed: Is 20°/s the maximum that can be reached without significant losses due to the lag angle? Have you, of curiosity, performed a similar analysis with a rotation speed of e.g. 35°/s? It would be interesting to state if this significantly influences the performance of the retrieved winds.

  It is our experience from real-world measurements that the SNR starts to degrade noticeably beyond 20°/s scan speed and becomes not usable beyond 45°/s. However, since we have not investigated this theoretically or systematically, we would like to avoid making statements in this direction. We now state that scan pattern optimization is an interesting point for future study.

- Page 8, line 191, “zenith”. Shouldn’t it be nadir, as you are downward looking?

  Absolutely, changed.

- Page 8, line 199: along/across-track components: Having these 4 LOS measurements (along and across track) would also be very beneficial for GW research, e.g. flux retrieval as recently shown in Witschas 2023.

  We have added a reference stating this.

- Page 11, line 262: Could you give examples of how the values change for each reference truth? Is it more cm/s or m/s? Would be helpful to read the numbers here.

  It is O(cm/s) but depends on altitude as well as scan pattern and retrieval strategy investigated. Generally speaking differences between triangular and square volume truth are always small with O(0.05 m/s). They are largest towards the top of the boundary layer where the truth volumes differ due to the triangular versus square shape of the volume.

  As expected, the nadir truth can show reduced error for the fixed-beam setup when the retrieval quality of the along-track components is investigated (O (0.2 m/s)). In this case, the measurements are conducted in a very confined volume close to the nadir truth. Thus, the retrieval error is lowered for the along-track components, but increased for the across-track components, when using the nadir truth. Since the nadir truth favors one component over the other we have decided on using the triangular volume reference truth which incorporates both retrieved components equally.

  We’ve included a statement on the order of magnitude in the revised manuscript now.

- Page 11, Eq. 1: What is MAE standing for? Is it mean absolute error?

  Yes, it is the mean absolute error, now stated also.

- Page 23: lines 536 ff: This is only true when equally separating the different LOS. What about an unequal separation e.g. by keeping the fore and aft beams? Have you ever considered such an option?

  So far we only simulated fixed-beam system with equidistant spacing for two reasons. First, the equidistant spacing maximizes the information added by each beam. Orienting beams closer together will lead to increased correlation between the measurements from different beams. Second, not constraining the system setup variation to symmetric options theoretically opens an infinite number of options due to the flexibility in azimuth and elevation. We believe this would be quite indigestible by the reader and therefore try to provide generalized results from which the effect of specific setups can be inferred. Our main lessons to do so are:

- Shallow elevation measurements and spatially co-located measurements help reduce retrieval error.
- Increasing the number of beams helps reduce azimuthal variation of retrieval characteristics and lowers the retrieval error overall.

We would like to thank Dr. Witschas again for taking the time and making a great effort in reviewing this manuscript. The comments provided above have certainly improved the quality of our manuscript and the discussion.

1 SNS5 vs. SNS13

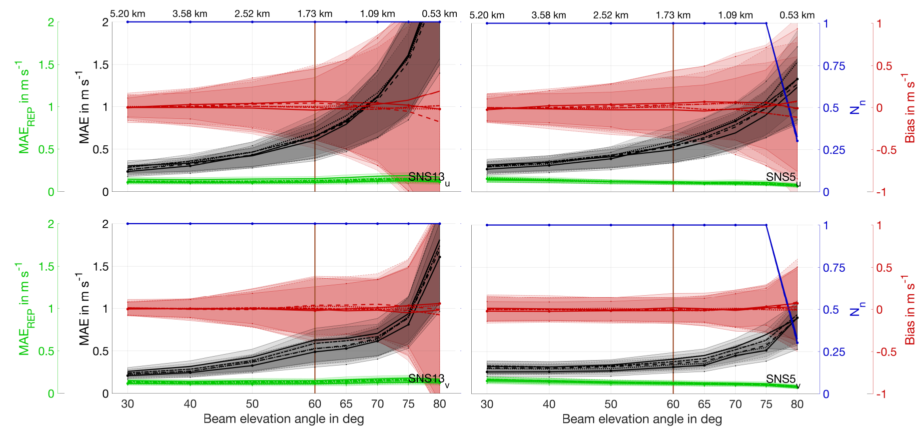

Figure 1: Retrieval quality parameters as a function of beam elevation angle for the standard SNS13 and SNS5 system flying in crosswind direction. Left panels: SNS13 system. Right panels: SNS5 system. Top panels: Across-track (u) component. Lower panels: Along-track (v) component.

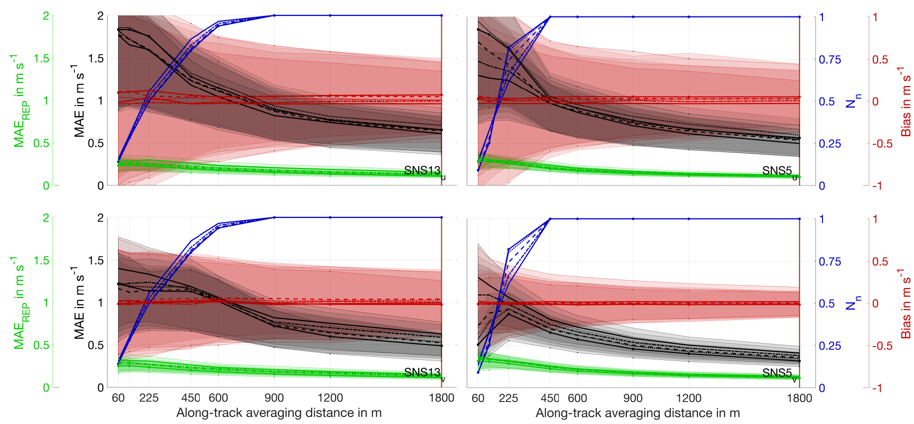

Figure 2: Retrieval quality parameters as a function of along-track averaging distance for the standard SNS13 and SNS5 system flying in crosswind direction. Left panels: SNS13 system. Right panels: SNS5 system. Top panels: Across-track (u) component. Lower panels: Along-track (v) component.