Review comments

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

Gasch, et al. 2023

Readability: Very well written; well organized and thorough.

Significance: Although the multiple fixed beam (each with its own lidar) is not novel for a proposed and simulated space based DWL (e.g. JEMCDL), the investment in another DWL tool for airborne atmospheric and ocean surface research is highly merited. Some advantages of a 5 FIXED beam (each continuous transmitting and receiving) compared with a scanning ADWL sampling in a cycloidal pattern using just a single transmitter/receiver for a certain subset of observational/research goals are obvious.

Methodology: Use of an LES-based airborne Doppler lidar simulation test bed is ideal for isolating sampling related errors of representing the "true" profile of the wind within a target volume in the presence of wind shear (both speed and directional) and turbulence. The attributions of "error" to turbulence or representativeness is very useful in operating and configuring an ADWL as well as processing the LOS retrievals to obtain estimates of the vertical profile of u and v within a dynamically non-homogeneous target volume, in this case the middle layers of an unstable PBL.

I am recommending that this paper be published after minor revisions. The revision I suggest is to acknowledge that SCA1 concept does not represent ADWL configurations currently in use by NASA, NOAA and ONR. SCA1 represents a simple continuous scanning mode suitable for this initial study.

We would like to thank Dr. Emmitt 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. Witschas. We hope that the manuscript is acceptable for both reviewers in the revised form.

Exceptions taken: Following is a discussion of exceptions taken to the experimental setup which raises issues with all subsequent conclusions.

1. The evaluation metrics in this paper are wind vector product centric. While this does not invalidate this papers investigation of the merits of FIX5 vs SCA1, a major utility of the ADWL observations is numerical model validation and numerical model Data Assimilation, both of which prefer LOS ADWL retrievals, leaving the full vector wind profile to second tier processing.

If LOS observation density and distribution in terms of along track and cross track directions were used for the basic comparisons, different conclusions could be reached as to which sampling technique serves the modeling community best.

Answer to 1.: In our opinion a vast majority of studies retrieve wind profiles from the measured LOS velocities, and we have now included a literature overview of studies doing so. Wind profile retrievals are needed for experimental and process-oriented studies since the pure LOS measurements are near-impossible to interpret with respect to their physical meaning. Hence, we put the focus on wind profile retrieval accuracy. Certainly, numerical model data assimilation could use the measured LOS observations directly, but we are unaware of studies which have done so up to date and therefore put the focus on wind profiling quality. We believe that a FIX5 system also is beneficial for the modelling community for three reasons: First, the system provides five times the amount of LOS data compared to a scanning beam system, allowing for better statistics and a more complete exploration of the retrieval volume. Second, the five stare directions are available without interruption, allowing for more reliable estimation of turbulent fluctuations alongside a simpler forward operator to compare model equivalents. Third, for a fixed-beam system the aircraft motion correction accuracy (largely determining LOS accuracy) does not depend on the pointing accuracy of the scanner and hence is expected to be more reliable. Additionally, we hope that the simpler fixed-beam design will allow more widespread and cost-effective ADL measurements, which will strengthen model evaluation and data assimilation in general.

Changes in the manuscript:

- Included literature overview on wind profiling studies.
- Since our study is focused on wind profiling retrieval accuracy we would like to avoid including statements or a discussion on model studies and data assimilation although we believe that the FIX5 system also offers advantages for these communities.

1. The scanning system (SCA1) does not represent the standard (traditional?) sampling pattern used with the ADWLs used in the studies referenced (Bucci, De Wekker) nor the ADWL used on the NASA DC8 (Turk, Kavaya). The coherent ADWLs being used in the USA in large field campaigns over that last 2 decades use two types of scanning:
    1. Fixed elevation with azimuthal scanning in a step-stare mode using 2 -13 azimuthal programmable stops (NASA's DAWN and the new AWP which includes a nadir staring option)
    2. ONRs (also used by NOAA) cylindrical side mounted scanner allowing programmable beam pointing routines within a large azimuth/elevation bounded target volume.
2. The use of a continuous scanning approach (e.g. at 20 degrees/sec) has been replaced with a "step and stare" strategy for many years and for several reasons (lag angle and the desire to eliminate the angular spread in lidar shots being integrated before preforming a spectral analysis).
3. A better (and more relevant) "reference" SCA1 for this sampling centric study would be the following based upon more than 1000 flight hours of observations using the cylindrical scanner:
    1. Elevation angle from the horizontal: 60 degrees
    2. 12 azimuthal stares for 1 second with 30 degree azimuth increments
    3. Slew rate between stares (30 degrees/second)

4. 1 nadir stare (five-10 seconds) in the middle of the 12 stare VAD.
5. 50m range resolution
6. 50 -100m along track averaging.

Answer to 1., 2., 3.: Summarizing the above 3 points, we agree that the continuous scan pattern based on G20 was idealized. We did not simulate a step-and-stare approach previously since the lidar internal signal processing is not simulated due to the idealized instrument simulation. Hence, staring does not improve radial velocity signal quality, as it would in a real-world system. Although continuous scans have been used (Augere et al., 2017) we acknowledge the point that the simulated scan pattern should correspond to more often used settings.

Based on the above points and the literature overview conducted by us we have replaced the former SCA1 pattern with a 13 point step-and-stare pattern (SNS13), with scan settings as suggested above. The new settings are as follows:

1. Elevation angle from the horizontal 60 degree.
2. 12 azimuthal stares for 1 second with 30 degree azimuth increments.
3. Negligible slew time between subsequent stares, further improving the step-and-stare pattern wind profile retrieval quality due to faster turnaround times.
4. 1 nadir stare of 1 second in addition to the 12 azimuthal stares (hence SNS13). The nadir time was shortened to 1 s to allow wind profile retrieval with reasonable turnaround times.
5. 30 m range resolution as before (higher than suggested, based on the expected laser performance of the fixed-beam system).
6. 100 m averaging for the radial velocity measurements for each stare direction (1 s stare time at 100 m/s). Averaging does not influence the radial velocity measurement accuracy since the lidar internal signal processing is not simulated (idealized instrument). The along-track averaging of the wind profile retrieval volume is varied between 60 m and 1800 m as before.

Changes in the manuscript:

- SNS13 scan pattern used and discussed including literature overview.

4. Had the SCA1 sampling pattern described in 3. above been used for quantifying the advantages (and disadvantages) of the FIX5 system, the following conclusions and expectations might be reversed or at least quantitatively changed.

Answer to 4.: We now simulate the scan pattern suggested above and thereby feel confident to address the below questions.

1. Line 35: The Goodness of Fit (GOF) value for a 12 look step stare solution for u,v provides a very useful measure of the non-uniform distribution of winds in the retrieval volume. This GOF is used to generate a confidence metric for representativeness. By performing triple pass processing a reasonable description of the non-uniformity can be made…not assumed except for the first pass.

Answer to 4.1: We assume that the GOF refers to the coefficient of determination (R^2) parameter which can be obtained from the inversion based fit to the measured radial velocities. However, as shown by G20, using the R^2 parameter for quality filtering can introduce unwanted bias in the wind speed retrieval at low wind speeds. Introduction of this bias by quality filtering occurs due to the mapping of vertical wind inhomogeneities into horizontal wind, it is explained in detail in G20. The same behavior described there is evident in the present study. Even without filtering with the R^2 the wind speed retrieval is biased at low wind speeds. Introducing R^2 filtering severely increase the bias but does not help in bringing the MAE down. To avoid a strongly biased wind speed retrieval, we avoid using the R^2 as a quality filtering parameter in this study.

Changes in the manuscript:

- Included statement in retrieval section.

2. Line 54: It is not clear why the simulation was not performed for an aircraft flying 500-1000 meters above the PBL top since that may be the preferred perspective on the PBL. For the reasons stated elsewhere in the paper, the "saftest" portion of the PBL to use for analysis is the 100-1000meter layer (middle of the PBL). That is understandable, but the horizontal data coverage from 3000m will be different than from 1500m.

Answer to 4.2: The aircraft is flying at 1500 m, the PBL height is 1100-1400 m. While the aircraft is flying at 1500 m, only wind profiles from 100-1000 m altitude are considered for the analysis, e.g. with the distance of 500 m as suggested. The reason is that we want to investigate the impact of turbulence on wind profiling error. Above 1000 m turbulence starts to decay noticeable in the LES since the PBL entrainment and detrainment zone is reached. As the higher altitudes do not represent turbulent conditions, we exclude them in the retrieval. Of course, higher flight altitudes can be simulated in the ADLS, they do not change the results significantly. For example, a higher flight altitudes of 1800 m leads to a slight reduction (< 10%) of error, whereas a lower flight altitude of 1100 m leads to a slight increase (<10%) of error. Flight level changes affect both scanning and fixed-beam approaches equally, hence changing flight altitude does not change the findings from our study.

3. Line 94: Are there any disadvantages of the FIX5 vs the SCA1 for PBL research? Would any of the stated advantages of the FIX5 ADWL change if the more relevant scanning ADWL configuration were used?

Answer to 4.3: We have not discovered relevant disadvantages of the FIX5 system so far. One thing that requires attention in real-world measurements is the inability to compensate the aircraft pitch, roll and yaw movement when using fixed-beam directions. However, this is deemed unproblematic as it can be corrected in post-processing and is standard for airborne Doppler radar measurements (Strauss et al., 2015; Gasch, 2021). In addition, an active stabilization of the nadir telescope may also be possible. Also, compared to a scanning system azimuthal resolution of the radial velocity measurements is lost. However, since the azimuthal radial velocity measurements are usually strongly correlated not much information is lost and we do not see a disadvantage in this. Additionally, the FIX5 system provides five times the amount of radial velocity information in general, since the five beams measure simultaneously.

4. Line 175: Step and Stare scanning greatly reduces the lag angle losses. This is not an issue for the reported study, though.

Answer to 4.4: We agree. We now simulate a SNS scan pattern, but since the simulation does not include the backscattering process lag angle losses were not an issue beforehand also.

5. Lines 330-365: Throughout this paper there are frequent references to the issue of alignment of the FIX5 scanning telescopes with the aircraft ground track (crabbing) and the wind direction. With the 12 look scanning ADWL (let's call it SCA2), there are numerous subsets of azimuth look angles that can be used for sector wind vector retrievals, for example, quadrant retrievals. Based upon the 4 wind profiles thus obtained, horizontal gradients and other estimates of non-uniform flow can be deduced and quantified. The presence of PBL jets and directional shear layers does not impact (degrade) the accuracy of the SCA2 profile retrievals as much as might be the case for the FIX5. This point raises issues with all subsequent conclusions.

Answer to 4.5: We now simulate a SNS scan pattern as suggested. Certainly, looking at the suggested quadrant retrievals may be interesting for future studies. However, based on the current results it is unclear if reliable retrieval of horizontal gradients is possible. To allow inference of gradients beyond the uncertainty of the retrieval error, the gradients probably would have to be very large. In the results seen so far, decreasing the retrieval volume size results in fewer measurements per retrieval volume and less azimuthal spread, causing a strong increase in retrieval error. Unfortunately, PBL flow is heterogeneous down to very small scales, thereby the homogeneity assumption used in the retrieval is not necessarily fulfilled better. Based on the current results we expect a similar behavior for the quadrant retrieval approach.

Changes in the manuscript:

- We now state that optimizing step-and-stare approaches as well as modified retrieval strategies also offers interesting potential and is worth investigating in the future (scanning section and conclusions).

6. Lines N/A: This paper does not discuss explicitly the ability to measure vertical velocity. The primary interest is in the impact that very local vertical motions associated with organized structures such as OLEs will have on the calculation of horizontal wind components. However, the DC offset of the 12 point solution along with the 5 – 10 second vertical stare provide insight to the scales of vertical "contamination" of the horizontal wind retrieval. This, at the least, provides a means of attaching "quality" flags to each profile. Without this "over sampling" compared to only 2-4 perspectives, there is much less basis for judging representativeness in actual applications.

Answer to 4.6: We understand that this point suggests using the residuals from the radial velocity based wind profile retrieval for an uncertainty analysis, in addition to the vertical wind measurements. We have tried to do so in Gasch (2021) and this is certainly an excellent point for future study. So far, it is quite complicated to convert the scales of contamination into a quantitative uncertainty estimation. In any case, data-driven uncertainty estimation should be possible with higher accuracy for a FIX5 system compared to a scanning system. More radial velocity information is available from a FIX5 system, hence the scales can be determined more reliably. We have decided against including a 5-10 second vertical stare in the step-and-stare pattern used in this study, since it would have increased scanner turnaround times and thereby coarsened the along-track resolution of the wind profiles noticeably. Instead, we include a 1 s vertical stare to match the duration of the other look directions.

Changes in the manuscript:

- We believe that an evaluation of the possibility of a data-driven uncertainty estimation is beyond the scope of this study but it has been mentioned by G20 as worthwhile to explore already.

1. In spite of the exceptions and concerns expressed in 5. above, this paper is well written and answers the questions (Lines 94-97) based upon the assumed SCA1 configuration. However, to be relevant to how ADWLs have been scanned for that last 20 years (like ONR's TODWL and NRL/NOAAs P3DWL with very flexible pointing options) and are being designed for the next generation of high energy ADWL (like NASA's AWP with a vertical stare option), there is the need to simulate a SCA2 type instrument and ask the questions a slightly different way. 1.) How do the FIX5 and SCA2 serve the modeling community vs the atmospheric processes community? (i.e. LOS as primary product vs wind vector profile?) 2.) Do fewer but more accurate bi and quad perspective profiles over smaller foot prints trump more LOS samples from more (say, 12) perspectives, especially in complex flows?

Answer to 1.: We have implemented the modified SNS scanning system as suggested and have addressed the points raised above. We also address the discussion on the value of wind profile vs. radial velocity measurements above. The additional points mentioned certainly provide excellent points of investigation for future studies but are beyond the scope of this study and would require more than minor changes, as suggested.

Regardless of any follow-on simulations, the development of the FIX5 instrument has merit and will not only provide collocated (for no crabbing) bi-perspective simultaneous LOS measures of the winds, but will also use SOTA fiber laser technology for each telescope and, hopefully, a less expensive and thus more available means of making airborne wind profiles for both academic research as well as applications. The increased number of vector profiles per km along a track is certainly attractive.

We would like to thank Dr. Emmitt again for taking the time and making a great effort in reviewing this manuscript. We are certainly excited to see the first measurements from the fixed-beam system and we hope that it will serve the community by providing new opportunities and insight.