04.10.2023

Review of the article

"First measurements of 3-Dimensional winds up to 25 km based on Aerosol backscatter using a compact Doppler lidar with multiple fields of view "

submitted by Mense et al.

(AMT)

Review Summary

The authors introduce the first 3D wind measurements up to the stratosphere based on an updated version of their VAHCOLI system. In particular, they extended the system by multiple telescopes that enable the simultaneous measurements of 4 LOS directions (N, S, W, E) as well as the vertical component. They demonstrate the functionality of the system based on an exemplary measurement and comparison to both ECMWF data as well as Aeolus data. The paper is well-structured and clearly understandable. Still, a few important pieces of information to interpret the presented results are missing. Furthermore, a few of the drawn conclusions are questionable. Hence, I recommend accepting the paper for publication in AMT after major revisions based on the comments that are listed below.

General comments

- Although it is appreciated that the VAHCOLI system is introduced in L Lübken and Höffner, 2021, it would be very helpful to recapitulate the overall measurement principle and the basic specifications, such that the presented results can be interpreted without going to other references.
- The term "ADM" was omitted by ESA several years ago. Since then, it is just Aeolus. This should be adapted throughout the manuscript.
- The paper title is a bit misleading, as it says that 3D wind measurements are demonstrated up to 25 km altitude, which is not true as only the north – south beams reach the 25 km, whereas this is not true for the east – west beam which only reach lower altitudes.

Detailed comments

- <u>Abstract:</u> A few acronyms are not introduced in the abstract (VAHCOLI, ECMWF)
- <u>Abstract:</u> You mention an excellent agreement between VAHCOLI and ECMWF data. Although I agree that a random error of < than 1 m/s is rather good, a systematic error of -0.93 m/s is not. Hence, I suggest to adapt this sentence.
- <u>Abstract, comparison to Aeolus:</u> At this stage, it is not clear what you compare here. For the ECMWF comparison, it is the HLOS for the north and south beam, but for Aeolus, it is likely to be a projection to the Aeolus viewing direction. This should be clarified here.
- <u>Line 39, Aeolus error estimates:</u> It should be emphasized that both the systematic but even more the random error of Aeolus Rayleigh clear winds depend on the actual signal levels and can reach values up to 7.5 m/s. Due to the decreasing signal levels throughout the mission, the overall random error increased. But also, in for instance dust-laden areas with lower signal levels, the random error can be significantly higher. This is for instance shown in Witschas et al. 2022, Fig. 8 by means of a statistical comparison to airborne wind lidar data. It

would be worth mentioning here and adding further references related to Aeolus wind product validation.

- Line 60, unique possibility to measure wind based on aerosol: It is not understood why you argue that this is a unique possibility. For instance, the ALADIN airborne demonstrator A2D measures wind with a similar technique to Aeolus and a rather good sensitivity due to the larger signal levels. Further, Ball Aerospace developed a wind lidar system based on a Mach-Zehnder (OAWL) interferometer that is very sensitive to aerosol return (Baider, 2018, The Optical Autocovariance Wind Lidar, Part II: Green OAWL (GrOAWL) Airborne Performance and Validation). Last but not least, heterodyne detection wind lidar systems demonstrated the ability to measure wind speed also in the vicinity of very weak aerosol concentrations. This should be appreciated here.
- Fig. 1: It would be helpful to indicate the respective parts (for instance the camera window) in the picture.
- Line 77, new approach: It is not agreed that the approach of using multiple FOV is really new. This was done in several other wind lidars before, for instance, "Narasimha S. Prasad, 2017 - Three-beam aerosol backscatter correlation lidar for wind profiling". This should be appreciated.
- Line 97: You mention the simultaneous measurement of u,v,w. This would also allow to directly derive the momentum flux from the data. Have you verified if this works properly?
- Line 111, carefully selected materials: Which are the materials that you selected, and why?
- Line 113, pointing precision: You mention that the pointing precision is only limited by the accuracy of the 3D print, but it is not mentioned how accurate the 3D printing is. Please adapt this information and mention the estimated pointing precision that results from this uncertainty.
- Line 140, icing problem and operation time: You mention that you had an icing problem during the discussed measurements but also that you have a further 600 hours of measurement data available. Hence, I was wondering if it would make sense to add a measurement case without an icing problem to demonstrate the maximum range the system can reach. I guess this would be a rather valuable extension.
- Line 143, Mie channel is used: Does the VAHCOLI system also has a Rayleigh channel? How far do you expect to reach with it?
- Fig. 2: You mention that you apply a running average of 2 hours in the horizontal and 1 km in the vertical, but the magenta area (right, top) shows features with a higher resolution. How is this possible? I would expect that these features smear out due to the averaging. Considering the moving average, what is the actual horizontal and vertical resolution of your data?
- Line 152: Fig 5 is mentioned and discussed before Fig. 4 is addressed. Maybe this should be rearranged.
- Line 155, Gaussian distribution: Here it would be worth mentioning that the spectral shape differs from a pure Gaussian in the lower troposphere (Rayleigh-Brillouin scattering) which will not impact your measurement results.
- Fig. 4, caption: How do you define your SNR? Further, you first mention the abbreviation SNR, before you explain it afterwards.
- Fig. 4, 5th line: top left should be bottom left.

- Fig. 4, caption, corresponding ECMWF winds: Do you interpolate ECMWF data to your measurement location, or do you use a next-neighbor approach which could also explain the discrepancies? Would be worth adding this detail. You write that in a later section, but the information should already be provided here.
- Fig. 5: freqency → frequency
- Line 206, separation of troposphere and stratosphere: It would be worth adapting the color-scale of the ECMWF data plot (e.g. by a factor of 10). With that, any features could be more easily recognized.
- Fig. 8: In my opinion, it would be interesting to see a scatter plot of ECMWF vs. VAHCOLI winds. The color of the data points could additionally indicate the altitude. By doing so, it could be demonstrated if there is for instance a systematic difference between the two data sets and how large the random error is.
- Line 223: but but, delete one
- Line 234, height-dependent bias: What is your explanation for the high-dependent bias? The discrepancy between the two beams? Isn't that much less important than the long averaging time? Do you also have radiosonde profiles that could be used for comparison? It would be interesting to clarify if there is an issue with the VAHCOLI wind retrieval or with the used reference data sets, e.g. ECMWF.
- Line 236, ff: As Aeolus data is assimilated in the ECMWF model, these two data sets are not really independent. This fact should be highlighted somewhere. Furthermore, it is important to add information on the Aeolus processor baseline that has been used. The Aeolus processor experienced a lot of modifications throughout the mission time, which also had an impact on the Aeolus data quality. In addition, it is not clear if you are using Rayleigh-clear winds or Mie-cloudy winds for your comparison.
- Line 239, 1 km integration: Usually, the Aeolus range bin size is variable. Do you take this into account, or do you "just" average to 1 km range gates?
- Line 241, drift correction: How large is this drift correction? Would be interesting to see the wind profiles before and after correction to get an idea about the actual impact of this correction procedure.
- Line 245, biggest differences in the stratosphere: Is this in line with the estimated error that is also reported in the Aeolus data product? As the signal levels for Ray-clear winds are lowest in the stratosphere, the estimated error should be large - as observed.
- Line 260: You conclude that the ECMWF model is underestimating wind gradients. Can you be really sure that the beam separation, the spatial and temporal discrepancy between lidar measurements and model, and the 2-hour average cannot introduce such discrepancies? Would be worth excluding all other potential error sources and adding for instance a radiosonde comparison that supports this statement.
- Fig. 11: Is this Aeolus Rayleigh-clear or Mie-cloudy winds or a mixture? It is not understood what you are comparing here.
- Line 263, Assimilation of high-quality winds: Are you referring to winds measured from ground-based lidar systems in the framework of a network here, or to upcoming spaceborne wind lidars as for instance Aeolus 2?
- Line 278: What is the overall goal of a wind lidar network?