Response to Referee Comment (RC2) on

Intercomparison of wind observations from ESA's satellite mission Aeolus and the ALADIN Airborne Demonstrator (https://doi.org/10.5194/amt-2019-431)

We appreciate the referee's very insightful and helpful remarks on our manuscript. The responses to the individual comments and the corresponding changes in the manuscript are presented in the following.

General Comment:

The paper by Oliver Lux and coauthors reports the results of an airborne campaign dedicated to Aeolus wind product validation using its airborne demonstrator A2D operating onboard Falcon aircraft together with DWL lidar. The presented cal/val experiment is an important contribution and a tremendous effort towards improvement of direct-detection sensing of wind from space. The paper is carefully written, the experimental setup and validation methodology are thoroughly and comprehensively described, the graphical material is prepared with care, whereas the conclusions and recommendations are well substantiated.

That said, the general issue of this paper, in my opinion, is that its content is excessively biased towards methodological aspects of the intercomparison. I assume that most potential readers of this article would be rather interested in the Aeolus validation part (since the airborne lidars and their performance are already described elsewhere), however they would have to read a long way to get to what they are looking for.

The title of the paper promises a long-awaited result of Aeolus validation using its airborne demonstrator within a dedicated validation campaign carried out by the renown experts in the off-ground lidar technique. However, the results of A2D-Aeolus validation are mixed together with the A2D-ECMWF-AEOLUS statistical figures. It gets worse when the key results of intercomparison are reported as lidars' biases with respect to ECMWF. This raises a valid question i.e. what the Falcon-Aeolus underflights are for, if both lidars are finally referenced to the model.

I recommend the authors to address the following remarks, in order to reconcile the inconsistencies between the title and the content.

Response to the General Comment:

We agree that there are inconsistencies between the title and the content of the paper in its originally submitted version, which primarily originate from the mixture of the results from the Aeolus validation using the A2D with model comparisons of both lidar instruments. We also share the opinion that the first part of the paper, especially the instrument description of the A2D (section 2.1) and the explanation of the response calibrations (section 3.1), are too long given the main focus of the article, namely the intercomparison of the A2D wind results with those of Aeolus. Therefore, we have shortened the two sections mentioned above to more concentrate on the methodology for adapting the A2D wind data to the Aeolus grid and viewing angle and on the wind comparisons. Nevertheless, we believe that it is important for the readers to understand the differences between the airborne and the satellite-borne wind lidar regarding the design and data acquisition, since these aspects are crucial for the understanding of the respective error sources and related limitations in terms of accuracy and precision. Furthermore, the assessment of the systematic and random error of the A2D by comparison with the 2-µm DWL and the ECMWF model is a prerequisite for the later derivation of the Aeolus accuracy and precision. This approach is not clearly formulated in the original version of the manuscript, but better presented in the revised version. In particular, following the referee's suggestion, we have separated the model comparisons from the lidar-lidar comparison (see also response to comment #2.4 below). Overall, we regard this paper as the basis for upcoming publications that will focus on the Aeolus validation during the operational phase of the mission. It is thus intended to present the necessary tools to be applied for making the wind data from the A2D (and other wind lidars) comparable with those of Aeolus, rather than to provide an extensive validation study. The latter will be the subject of forthcoming publications dealing with the airborne campaigns conducted in May and September 2019 which also yielded a much larger data set.

In order to remedy the deficiencies of the paper, we have revised it according to the reviewer's comments. The responses to the individual comments and the related changes to the manuscript are elaborated below.

Comment #2.1:

In the introduction (l.57-58), the authors claim their study a methodological reference for the airborne experiments on Aeolus validation. With that, the cal/val experiment is restricted to Rayleigh wind measurements. What are the other clear-air airborne Doppler lidars involved in Aeolus validation? If there are none, this methodological reference could be restricted to internal use. Please be more specific regarding the scope of potential applications of the presented methodology.

Response to Comment #2.1:

The methodology described in the manuscript is not only applicable (and necessary) for the A2D, but also any other Cal/Val instrument that measures only one LOS component of the wind vector. One example is the *LEANDRE New Generation* (LNG) which was developed at the *Laboratoire Atmosphères, Milieux, Observations Spatiales* (LATMOS). The three-wavelength-dual-polarization-backscatter lidar is based on a two-wave Mach–Zehnder interferometer and is, amongst others, capable of measuring line-of-sight wind speeds (Bruneau et al, 2015). The instrument is foreseen to be deployed on airborne campaigns for the Aeolus validation and was already used in pre-launch campaigns during NAWDEX (Schäfler et al., 2018) on coordinated flights with the DLR Falcon. Intercomparison of the LNG wind data with the Aeolus winds will necessitate the consideration of the different viewing geometries, as it is the case for the A2D. In this respect, the study can be regarded as a methodological reference for upcoming publications on the Aeolus validation by means of the A2D, LNG or other wind lidars without the capability to retrieve the entire wind vector.

The introduction was specified along these lines in order to stress the relevance of the shown methodology:

More specifically, it is shown how to take account of the different LOS directions in order to make the wind data sets comparable. This procedure is not only required for the A2D, but any other Cal/Val instrument that measures only one component of the wind vector, such as e.g. the LEANDRE New Generation (LNG) (Bruneau et al., 2015) which is also foreseen to be deployed on airborne campaigns for the Aeolus validation.

The following reference was added:

Bruneau, D., Pelon, J., Blouzon, F., Spatazza, J., Genau, P., Buchholtz, G., Amarouche, N., Abchiche, A., and Aouji, O.: 355-nm high spectral resolution airborne lidar LNG: System description and first results, Appl Opt, 54, 8776–8785, doi:10.1364/AO.54.008776, 2015.

Moreover, the following sentence was added to the conclusions section:

This procedure is not only of relevance for future validation campaigns employing the A2D, but also other wind lidars without the capability to retrieve the entire wind vector.

Comment #2.2:

The key example of Aeolus-A2D intercomparison is presented in Fig. 9, however the panels a) and c) are difficult to compare as they are interspersed by the panel 9b, which should belong to the section describing the intercomparison setup.

Response to Comment #2.2:

See Response to Comment #2.3.

Comment #2.3:

Apart from the spatial curtains in Fig. 9, it would be useful to show a few examples of individual wind profiles measured by both lidars, probably also at their native vertical resolution. This will give a much better feeling on the capacities of different lidars than the tabulated numbers.

Response to Comment #2.3:

We agree with the reviewer's comments #2.2 and #2.3, and have revised Fig. 9 of the manuscript (see below). The panels (a) to (d) have been re-sorted such that the original A2D Rayleigh wind curtain after adaptation to the Aeolus grid but without azimuth correction is placed on the left-hand side of the figure together with the ECMWF model winds (from the Aeolus L2C product). The latter serve to apply the azimuth correction, as explained in section 4.1 of the manuscript, to produce the azimuth-corrected A2D wind curtain shown in panel (c). The Aeolus L2B Rayleigh wind curtain is plotted just below (panel (d)) which facilitates the comparison of the two. Moreover, the wind profile for one selected Aeolus observation is shown in an added panel (e) together with the corresponding profiles of the other three datasets. Here, the error bar for the Aeolus winds (blue squares) represents the estimated error included in the L2B product, while the error bar for the azimuth-corrected A2D winds (green dots) corresponds to the weighted standard deviation of the A2D winds from those bins that overlap with the respective Aeolus bin. Comparison of the wind profiles not only demonstrates the necessity of the azimuth correction, but also shows the good agreement of the Aeolus winds with the A2D and model data within the error margins.

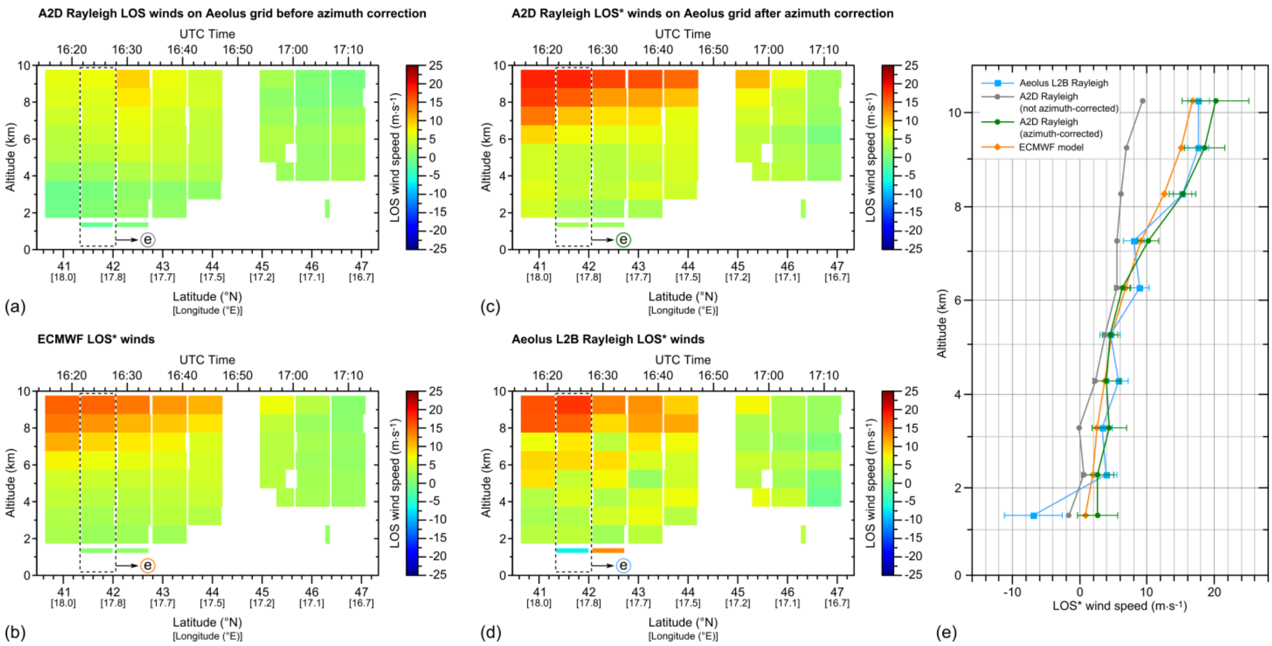

Figure 1. LOS* wind profiles obtained during the underflight on 22 November 2018 between 40.5°N and 47.2°N: (a) A2D Rayleigh winds averaged onto the Aeolus measurement grid and for an off-nadir angle of 37°, but without azimuth correction, (b) ECMWF model winds, (c) A2D Rayleigh winds with azimuth correction and (d) Aeolus L2B Rayleigh winds. White colour represents missing or invalid data of one of the two instruments, e.g. below dense clouds. Only Aeolus Rayleigh LOS* winds with an estimated error below 4.8 $m\cdot s^{-1}$ were considered valid. The wind profile for one selected Aeolus observation is shown in panel (e) together with the corresponding profiles of the other three datasets. The error bar for the Aeolus winds (blue squares) represents the estimated error included in the L2B product, while the error bar for the azimuth-corrected A2D winds (green dots) corresponds to the weighted standard deviation of all A2D bins contributing to the respective Aeolus bin. For the uncorrected A2D winds (grey dots), the error bars were omitted for the sake of clarity.

We refrained from plotting the A2D wind profile in its original vertical resolution, since the azimuth correction procedure, in its current state, is only applicable after adaptation of the A2D data onto Aeolus grid. This is because the Aeolus L2C data (ECMWF model output on Aeolus measurement track), in particular the *u* and *v* components, are provided on that same grid. Hence, either higher resolution model data or interpolation of the L2C data onto the A2D grid would be required to apply the azimuth correction to the A2D data in its native resolution. Furthermore, since there are on average around 20 A2D observations within the range of one Aeolus observation, we think that it is more representative to show the weighted wind speed average of all observations instead of selecting one particular observation out of the set of 20.

The modified version of Fig. 9 was included in revised manuscript and discussed in section 4.2 as follows:

The left part of the figure shows the A2D Rayleigh winds averaged onto the Aeolus measurement grid and for an off-nadir angle of 37°, but without azimuth correction (panel (a)) and the Aeolus L2C Rayleigh winds, i.e. LOS* winds based on ECMWF model data (from the Aeolus L2C product) (b). The A2D Rayleigh winds after azimuth correction (A2D LOS* winds) (c) and the Aeolus L2B Rayleigh winds (d) are depicted in the middle of Fig. 9.

Moreover, the wind profile for one selected Aeolus observation is shown in panel (e) together with the corresponding profiles of the other three datasets. Here, the error bar for the Aeolus winds (blue squares) represents the estimated error included in the L2B product, while the error bar for the azimuth-corrected A2D winds (green dots) corresponds to the weighted standard deviation of the A2D winds from those bins that overlap with the respective Aeolus bin. Only Aeolus LOS* winds with an estimated error below 4.8 m·s^{-1} (HLOS: 8 m·s^{-1}) were considered valid. Comparison of the curtain plots and the selected wind profiles demonstrates the necessity of the azimuth correction. Due to the strong meridional wind especially in the upper range gates of the A2D at the beginning of the common leg, large wind speed differences Δ > 5 m·s^{-1} were present between Aeolus and the uncorrected A2D data (grey dots) which were compensated by the azimuth correction as explained above. Hence, the adapted A2D Rayleigh winds show much better agreement with both the Aeolus Rayleigh winds and the model data. The weighted standard deviation of the A2D winds, indicated by the error bars, represents a measure of the variability of the A2D winds within the compared Aeolus bin. The values are on the order of 2 to 4 m·s^{-1} and determined by both the random error of the A2D as well as the horizontal and vertical wind gradients within the respective Aeolus bin.

Comment #2.4:

The results of A2D-Aeolus intercomparison should be presented in a separate section devoted to lidar-lidar intercomparison. The key figures of Aeolus-A2D intercomparison statistics (which is the title of the paper) should be provided in the abstract and conclusions. The comparison against ECMWF should be reported in a specific subsection of the manuscript.

Response to Comment #2.4:

Following the reviewer's suggestion, we have separated the model comparisons (section 4.3) from the lidar-lidar intercomparison (section 4.4). For this purpose, the figures showing the scatterplots from the three-dataset comparison for the selected wind scene on 22 November 2018 (Fig. 10) and the entire campaign (Fig. 11) were re-sorted. In the revised manuscript, there are three figures with two scatterplots each, depicting the A2D-to-model, the Aeolus-to-model and the Aeolus-to-A2D statistical results for the selected wind scene and the entire campaign, respectively. The discussion of the mutual comparisons has been adapted to the new structure accordingly.

In addition, the key figures of the Aeolus-to-A2D comparison statistics were added to the abstract and conclusions. In particular, the abstract of the revised manuscript includes the following sentences:

The statistical comparison of the two instruments shows a positive bias of the Aeolus Rayleigh winds with respect to the A2D Rayleigh winds of 2.6 m·s^{-1} and a standard deviation of 3.6 m·s^{-1}. Considering the accuracy and precision of the A2D wind data which was determined from the comparison with a highly-accurate coherent wind lidar as well as with ECMWF model winds, the systematic and random error of the Aeolus Rayleigh winds is determined to be 1.7 m·s^{-1} and 2.5 m·s^{-1}, respectively.

In the conclusions section, the following sentences were added:

The statistical comparison revealed biases of -0.9 m·s^{-1} and +1.6 m·s^{-1} for the A2D and Aeolus LOS* Rayleigh wind speeds with respect to the ECMWF model, respectively. Intercomparison of the two wind lidars showed a positive bias of the Aeolus Rayleigh winds with respect to the A2D of 2.6 m·s^{-1}, while the spreading between the two data sets of 3.6 m·s^{-1} results from the respective random errors that add up quadratically. Considering the systematic and random error of the A2D, the accuracy of the Aeolus Rayleigh winds is determined to be +1.7 m·s^{-1} and 2.5 m·s^{-1} which is in line with the results from other validation studies performed for the commissioning phase of the Aeolus mission (Khaykin et al., 2019; Witschas et al., 2020).

<u>Comment #2.5:</u>

The discussion on the representability of the Aeolus cal/val results could be better developed in the context of the preliminary nature of L2B wind product.

<u>Response to Comment #2.5:</u>

The following paragraph was added to the discussion of the lidar-lidar-comparison:

In conclusion, due to the preliminary nature of the Aeolus L2B wind product, the Rayleigh winds exhibit relatively large systematic and random errors which are higher than the mission requirements (ESA, 2016). However, it should also be stated, that the representativity of the statistical results shown here is limited by the relatively small data set obtained from the WindVal III validation campaign. A strategy for increasing the number of compared winds, and hence the representativity of the Aeolus Cal/Val results in forthcoming campaigns is described in section 4.6.