

Aeolus validation with the DLR airborne Doppler wind lidars: 2- μm heterodyne detection and 355 nm ALADIN Demonstrator

Christian Lemmerz^{(a)*}, Oliver Lux^(a), Benjamin Witschas^(a), Stephan Rahm^(a), Alexander Geiß^(b),
Andreas Schäfler^(a), Uwe Marksteiner^(a), and Oliver Reitebuch^(a)

^(a)*Institute of Atmospheric Physics, Deutsches Zentrum für Luft- und Raumfahrt (DLR),
Oberpfaffenhofen 82234, Germany*

^(b)*Ludwig Maximilians University, Munich, Germany*

**christian.lemmerz@dlr.de*

Abstract: In the three years after the launch of ESA's wind lidar mission Aeolus in 2018, DLR conducted four airborne campaigns to validate its wind products. The DLR Falcon aircraft was equipped with two Doppler wind lidar (DWL) instruments, the ALADIN Airborne Demonstrator (A2D), the prototype of the Aeolus instrument, and a scanning heterodyne detection 2- μm DWL as a reference system. These instruments were operated concurrently for over 26,000 km along the Aeolus measurement track. Complementary and synergistic observations from both DWLs were used to characterize systematic and random wind errors of the Aeolus products, and to recommend algorithm improvements. Recently, the data obtained from campaigns in Iceland (2019) and Cape Verde (2021) was applied to validate reprocessed Aeolus wind products (Baseline 16). This paper provides an overview of the airborne validation campaigns and ongoing contributions to the Aeolus performance validation and processor evolution.

1. Introduction

Aeolus was the first DWL in space and provided profiles of horizontal wind speed along its orbit. Launched in August 2018, its single payload was the Atmospheric LAsER Doppler INstrument (ALADIN) based on two spectrometers analyzing the wind of atmospheric return backscattered by molecules (Rayleigh channel) and by particles (Mie channel) along the line-of-sight (LOS) [1]. Already several years before launch, DLR developed the A2D together with ESA and Airbus DS, for preparing the mission. The A2D features a high technological communality with the ALADIN design including its detectors and spectrometers from the pre-development program, combined with a frequency stable and tunable ultraviolet (UV) laser. In combination with the scanning 2- μm DWL as a reference, several atmospheric measurement campaigns were conducted from ground and onboard the DLR Falcon. Resulting data-sets were the basis for building expertise on the new ALADIN direct detection technology, for deriving a mature processing suite for the calibration and wind measurement modes, and for the demonstration of airborne in-orbit performance validation concepts [2]. During the Aeolus mission lifetime of almost five years,

this knowledge contributed to the instrument performance monitoring and improvement operations within the Aeolus Data Innovation and Science Cluster (DISC) [3-5], as well as to four airborne validation campaigns in different phases of the mission [6]. The campaign results are currently used to assess the reprocessed Aeolus data and continue to support the future algorithm evolution in phase F, planned until end of 2028. First results of the reprocessed baseline B16 evaluation are reported.

2. Airborne Validation Overview

The heterodyne 2- μm DWL developed at DLR has a step-and-stare scanner and is based on the Lockheed-Martin Coherent Technologies Mag-1a lidar head. A vertical resolution of ~ 100 m and the high sensitivity to particulate backscatter usually provides good quality data (precision < 1 m/s) even in atmospheric conditions, where Aeolus and A2D detect only clear-air (Rayleigh) signal, allow to characterize the performance of both ALADIN channels. Additionally, exploiting its wind direction profiling capability from the conical scan pattern (usually set at 20° off-nadir, 15 - 21 LOS/scan) the 2- μm DWL acts as a reference for the A2D when flying both systems on the same aircraft. Hence, it

was utilized for the A2D characterization, which has similar limitations as ALADIN concerning vertical range resolution, spectrometer response stability and single-LOS geometry (20° off-nadir). But, flying along-track beneath Aeolus for validation, the lower aircraft speed provides a higher horizontal resolution for both DWLs. The concept is shown in Figure 1. The length of an Aeolus underflight was usually 700 km – 1500 km, limited by the air-craft range. During the four validation campaigns, a total of ~26,400 km was covered in parallel. For more details on the flight tracks and lidar systems, as well as the data compare-son strategy, please refer to [6] and the references therein.

The data obtained with the campaigns made it possible to evaluate the performance of Aeolus and the respective operational processing chain baselines in short time and to provide feedback to the validation and processor development communities accordingly. As can be seen from Figure 2 and the insert (Table 1), the campaign slots covered different Aeolus performance states concerning active lasers (FM-A and -B), laser energy (PD74), atmospheric (ATM) and internal (INT) signal strengths and were also conducted with dedicated range-bin-settings (RBS) activated for the campaign time and target areas. Aeolus wind measurements are

usually used for a statistical comparison with airborne data, averaged to the Aeolus grid. For comparison between the airborne and Aeolus DWLs coverage and resolution, an underflight example of the Iceland campaign, with the best Aeolus return signal (ATM) performance in 2019 is shown in Figure 3. Here, the Aeolus wind products from the recently released reprocessed baseline B16 are plotted.

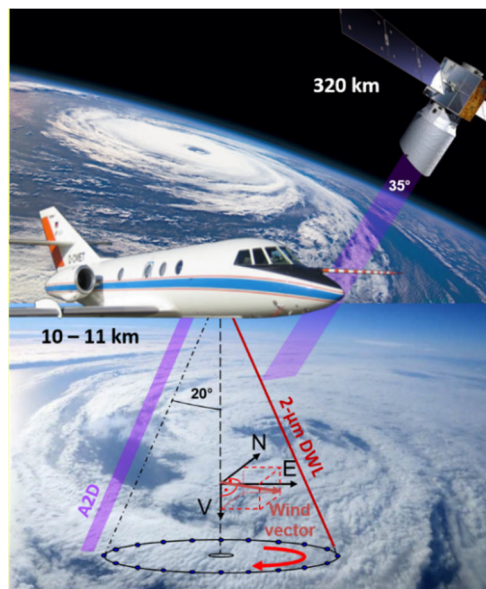


Figure 1. Aeolus and Airborne DWLs validation set-up

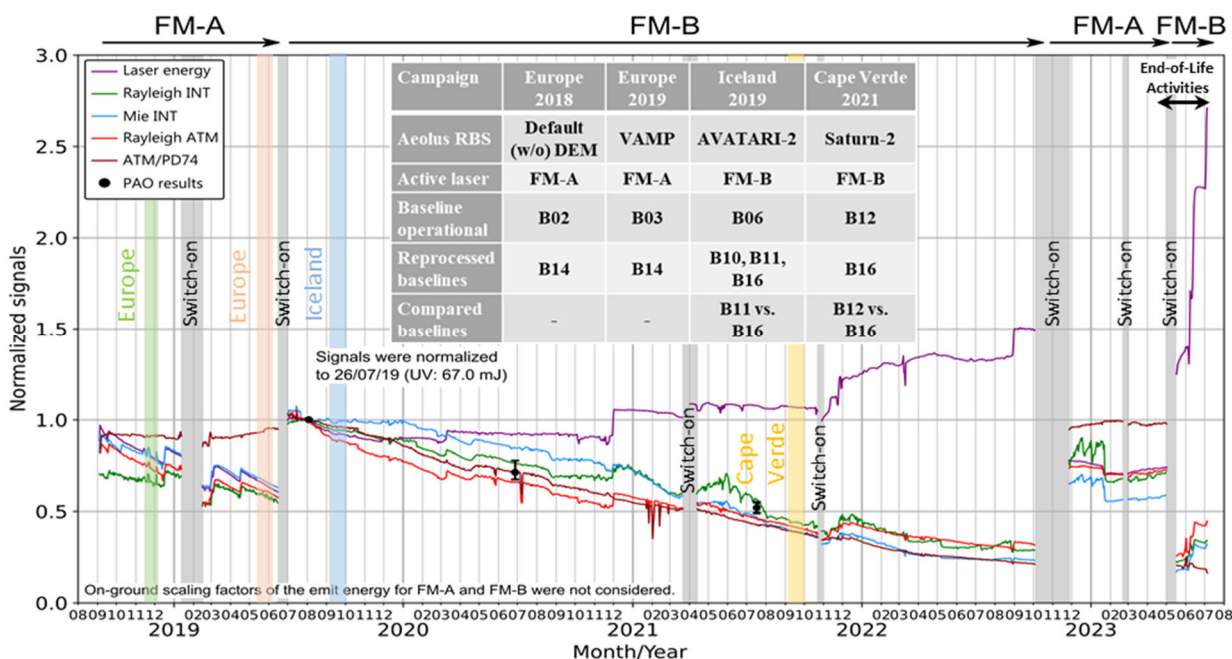


Figure 2. Aeolus signal performance evolution (based on DISC analysis O. Lux and K. Schmidt) with highlighted times and regions of the four airborne campaigns (see colored vertical bars). Table 1 (insert). Overview of the DLR validation campaigns and the corresponding main Aeolus operational and processor settings.

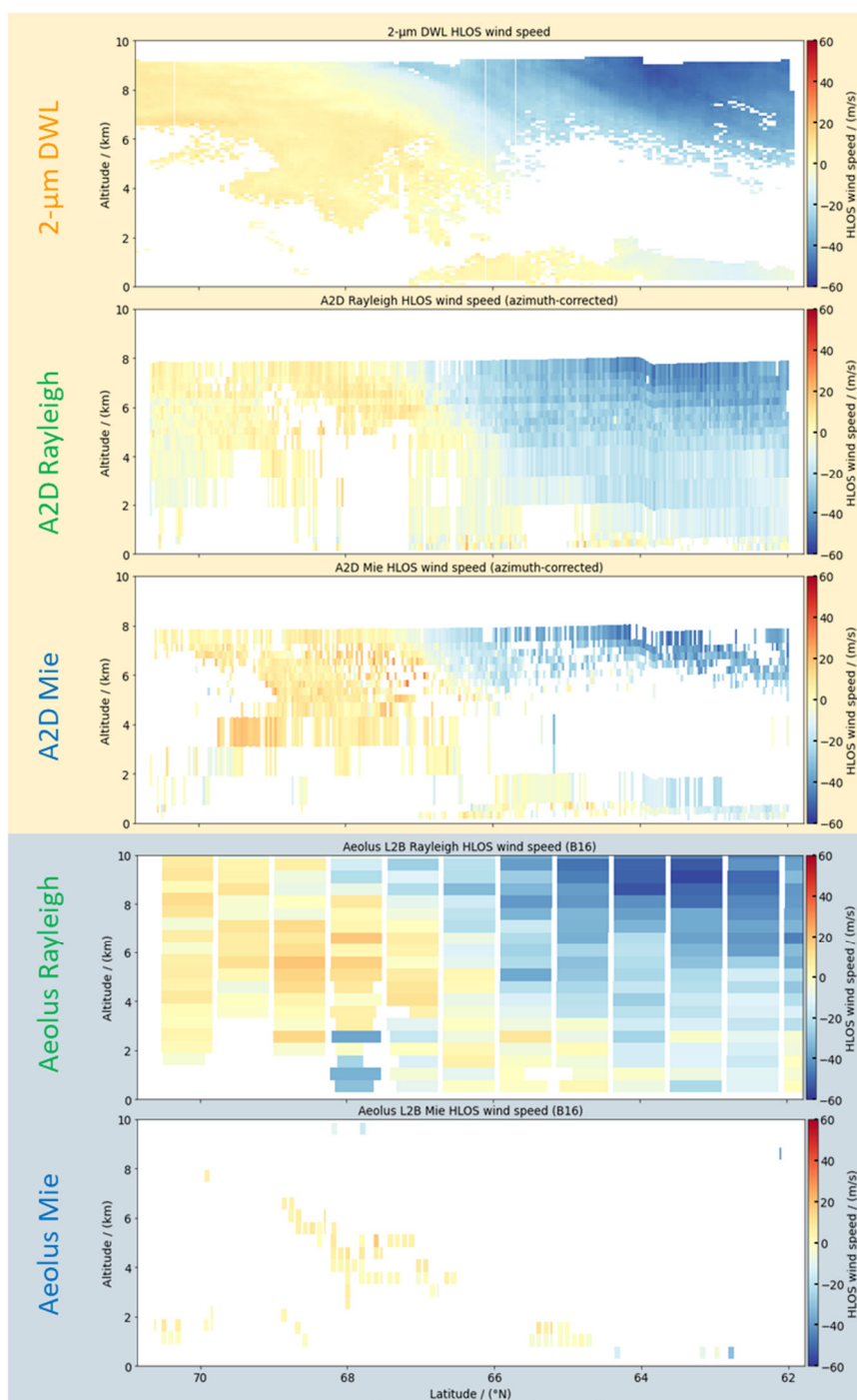


Figure 3. (Top) Airborne DWLs wind products derived for the Aeolus horizontal line of sight (HLOS) along the co-located underflight in Iceland on 16/09/2019 for comparison with the Aeolus Rayleigh and Mie Level 2B winds of B16 (4th reprocessing) in the airborne DWL altitudes.

3. Validation Results and Summary

For a quality evaluation and statistical comparison of airborne DWL data from the airborne validation campaigns with Aeolus level 2B wind products (Rayleigh-clear, Mie-cloudy) up to B11 and B12 reprocessed data, please refer to [7] and [8] with the references therein. To inform the Aeolus validation and processing communities, we can report here shortly about

recent findings concerning based on B11 and operational B12 comparisons of the Iceland, respectively, Cape Verde airborne data with the B16 release (covering the FM-B period from summer 2019 to autumn 2022). For Mie-cloudy winds, the estimated error (EE) product has slightly increased (< 1 m/s) on average and fewer gross errors are now more symmetrically distributed. Thus, the bias validation is less dependent on the EE-based QC-threshold. The

number of valid Mie-cloudy winds has substantially increased (up to 30%), and also Rayleigh-clear winds coverage has gained (~ 15%). However, comparing the 2- μm DWL and A2D Mie channel coverage with Aeolus Mie-cloudy in Figure 3, there is still room for further improved coverage, especially in this phase of the mission with the best performance. This task in the ongoing processor development by the Aeolus DISC, will be supported by the campaign data analysis. The Rayleigh-clear EE has significantly increased (up to ~2 m/s on average, depending on SNR) and is considered to be more realistic now. A low number of gross errors and their homogeneous distribution leads to the recommendation to only use the modified Z-score as QC-criterion for both wind products. Biases are stable within the uncertainty, random errors improved for both channels, showing best performance results of 5.4 m/s (-9%) and 3.2 m/s (-30%) for Rayleigh-clear and Mie-cloudy, respectively, during the Iceland campaign (B16 compared to B11). As the bias correction for Aeolus wind products is using a global scale model-based correction, it is possible to find higher biases on smaller scales. Thus, it is recommended to validate ascending and descending orbits independently. Inter-comparisons of validation results require considering the corresponding mean RBSs and EE-conditions, especially for Poisson-noise-limited (~SNR) Rayleigh channel results.

The DLR airborne activities from pre-launch to in-orbit validation have considerably contributed to the success of the Aeolus mission, which convincingly demonstrated the DWL concept including a substantial improvement of weather prediction quality. Further improvements of the Aeolus processors are expected and will be supported by the campaign data processing, analysis and technological expertise. The heterodyne 2- μm DWL and direct-detection A2D have proven to be efficient partners in the wind lidar development. This and the complementary and synergistic coverages are a role model for the preparation and validation of the Aeolus follow-on mission and give an outlook to what could be achieved with a potential hetero-technological DWL constellation, possible in the EPS-Aeolus-2 window of-opportunity.

4. Acknowledgements

This work was supported by DLR and ESA under contract no. 4000129946/20/NL/IA.

5. References

- [1] European Space Agency ESA, “ADM-Aeolus Science Report,” ESA SP-1311, 121 pp. (2008).
- [2] C. Lemmerz, O. Lux, B. Witschas, S. Rahm, U. Marksteiner, A. Geiß, F. Weiler, O. Reitebuch, „Airborne Doppler wind LIDAR technology demonstration for Aeolus: from pre-launch campaigns to mission performance validation,” International Conference on Space Optics—ICSO 2022 (12777/72-84), SPIE (2023).
- [3] I. Krisch, O. Reitebuch, J. von Bismarck, T. Parrinello, M. Rennie, F. Weiler, D. Huber, J. de Kloe, A. Dabas, A.-G. Straume, S. Abdalla, S. Aprile, S. Bley, F. Bracci, S. Bucci, M. Cardaci, W. Damman, D. Donovan, F. Ehlers, F. Fabre, T. Flament, P. Fischer, L. Isaksen, S. Jupin-Langlois, G. Gostinicchi, T. Kanitz, A. Lacour, M. de Laurentis, C. Lemmerz, O. Lux, U. Marksteiner, G.-J. Marseille, N. Masoumzadeh, M. Meringer, S. Niemeijer, I. Nikolaus, G. Perron, B. Pijnacker-Hordijk, K. Reissig, M. Savli, K. Schmidt, A. Stoffelen, D. Trajon, M. Vaughan, M. Veneziani, C. de Vincenti, B. Witschas, “The Aeolus Data Innovation and Science Cluster,” International Geoscience and Remote Sensing Symposium (IGARSS), Brussels, Belgium, 759-762 (2021).
- [4] O. Lux, C. Lemmerz, F. Weiler, T. Kanitz, D. Wernham, G. Rodrigues, A. Hyslop, O. Lecrenier, P. McGoldrick, F. Fabre, P. Bravetti, T. Parrinello, and O. Reitebuch, “ALADIN laser frequency stability and its impact on the Aeolus wind error,” *Atmos. Meas. Tech.*, (2021).
- [5] B. Witschas, C. Lemmerz, O. Lux, U. Marksteiner, O. Reitebuch, F. Weiler, F. Fabre, A. Dabas, T. Flament, D. Huber, M. Vaughan, “Spectral performance analysis of the Aeolus Fabry-Pérot and Fizeau interferometers during the first years of operation,” *Atm. Meas. Tech.* 15, 1465–1489 (2022).
- [6] C. Lemmerz, B. Witschas, O. Lux, S. Rahm, K. Schmidt, U. Marksteiner, A. Geiß, A. Schäfler, F. Weiler, O. Reitebuch, “Validation campaigns for Aeolus with the ALADIN Airborne Demonstrator and 2- μm Doppler wind lidar team,” 21st Coherent Laser Radar Conference (CLRC-21), 2022, proceedings (2023).
- [7] B. Witschas, C. Lemmerz, A. Geiß, O. Lux, U. Marksteiner, S. Rahm, O. Reitebuch, F. Weiler, “Validation of the Aeolus L2B wind product with airborne wind lidar measurements in the polar North Atlantic region and in the tropics,” *Atmos. Meas. Tech.*, 15, 7049–7070 (2022).
- [8] O. Lux, B. Witschas, A. Geiß, C. Lemmerz, F. Weiler, U. Marksteiner, S. Rahm, A. Schäfler, O. Reitebuch, “Quality control and error assessment of the Aeolus L2B wind results from the Joint Aeolus Tropical Atlantic Campaign,” *Atmos. Meas. Tech.*, 15, 6467–6488 (2022).