ADM-Aeolus pre-launch activities and recent advances in spaceborne and airborne Wind Lidar Systems

Benjamin Witschas, Fernando Chouza, Christian Lemmerz, Uwe Marksteiner, Stephan Rahm, Oliver Reitebuch

DLR, Institute of Atmospheric Physics, Oberpfaffenhofen, Germany

Benjamin.Witschas@dlr.de

Abstract: The first space-borne wind lidar mission ADM-Aeolus from ESA is currently scheduled for launch by mid-2017. For the preparation of the Aeolus validation, an airborne field experiment was performed during 3 weeks in May 2015 with the DLR Falcon and the NASA DC-8 aircraft. For the first time 4 wind lidars were deployed during an airborne campaign including two coherent and two direct-detection wind lidars at a wavelength of 2µm and 355 nm. A total of 7 coordinated flights of the Falcon and DC-8 yielded an extensive dataset.

Additionally, DLR's airborne coherent Doppler Wind Lidar was recently deployed in 3 coordinated airborne campaigns aiming to investigate the life cycle of gravity waves from ground up to the mesosphere. The horizontal and vertical wind measurements of the lidar provide valuable data for characterizing tropospheric gravity waves and background wind conditions.

1. Introduction

The global measurement of vertical wind profiles remains to be of highest priority for the needs of numerical weather prediction in order to improve the quality of weather forecast and climate studies. The European Space Agency ESA implemented the Atmospheric Dynamics Mission Aeolus (ADM-Aeolus) which is planned for launch by mid-2017 to demonstrate that this gap for wind profiles in the global observing system can be filled by a spaceborne wind lidar [1]. Aeolus carries the unique direct-detection Doppler wind lidar ALADIN that operates at an ultraviolet wavelength of 355 nm and makes use of two types of spectrometers to measure frequency shifts from molecular and aerosol backscatter [2]. For the purpose of validating the instrument concept and retrieval algorithms before launch, an airborne prototype, the ALADIN Airborne Demonstrator (A2D), was developed by DLR [3,4]. The A2D is the first airborne direct-detection Doppler lidar and in operation since 2005, having performed several airborne and ground-based campaigns together with a coherent-detection 2-µm wind lidar serving as a reference system [5]. The last airborne campaign (WindVal) on DLR's Falcon aircraft took place over the North Atlantic, Iceland and Greenland together with the NASA DC-8 aircraft in May 2015. For the first time 4 airborne wind lidars were flown in coordination.

In addition to the WindVal campaign, the 2 µm Doppler Wind Lidar (DWL) was deployed during 3 airborne campaigns dealing with the investigation of the life cycle of gravity waves namely the GW-LCYCLE I campaign (Kiruna, Sweden, December 2013), the DEEPWAVE campaign (Christchurch, New Zealand, June/July 2014) [6] and the GW-LCYCLE II campaign (Kiruna, Sweden, January/ February 2016). Gravity waves (GWs) are well known phenomena in the atmosphere and have a strong impact on vertical transport and exchange of energy and momentum between the troposphere and the middle atmosphere [7]. While there is a general understanding of processes launching GWs, the nature of wave source spectra less well-understood. Thus, a better characterization of GW sources is an outstanding issue for a proper description of the dynamical coupling of the lower and middle atmosphere. In order to characterize gravity waves excited over orography, horizontal and vertical wind measurements with high resolution and a low statistical uncertainty of several 10 cm/s are desired, where all of these goals can be reached with the DWL.

In this paper, the first wind lidar mission ADM-Aeolus will be introduced and first results from the pre-launch validation campaign WindVal in the North Atlantic from 2015 with the DLR Falcon and NASA DC-8 aircraft will be shown. Subsequently, a short overview of recent advances in airborne wind lidar observations related to the investigation of gravity waves is given.

2. Wind validation campaign (WindVal) in preparation for ADM-Aeolus

Two aircrafts with 2 different wind lidar systems on-board were operated from Keflavik airport in May 2015. The DLR Falcon aircraft consisted of the A2D [2-4] and the 2 µm DWL [8-10]. The NASA DC-8 was equipped with the DAWN (Doppler Aerosol Wind) [11], TWiLiTE (Tropospheric Wind Lidar Technology Experiment) [12] and a dropsonde unit from Yankee Environmental Systems [13]. In addition to the airborne instruments, a ground-based wind lidar was deployed at the Greenland Summit Station (72.58°N, 38.48 W, 3216 m ASL). This station releases 2 radiosondes per day and is equipped with an aerosol lidar from the MPL (micro-pulse lidar) network. The NCAS (National Centre for Atmospheric Science) Doppler Aerosol lidar (Halo Photonics) operating at a wavelength of 1.55 µm collected data continuously at the Summit station from May 1, 2015 to June 27, 2015. The objective was to characterize the backscatter and wind conditions close to the surface (e.g. blowing snow, diamond dust), which is of relevance specifically during response calibrations for the ALADIN. Both aircrafts were operated from May 11 to May 28, 2015 with a total of about 35 flight hours for the DLR Falcon aircraft and 50 flight hours for the NASA DC-8 (Fig. 1).

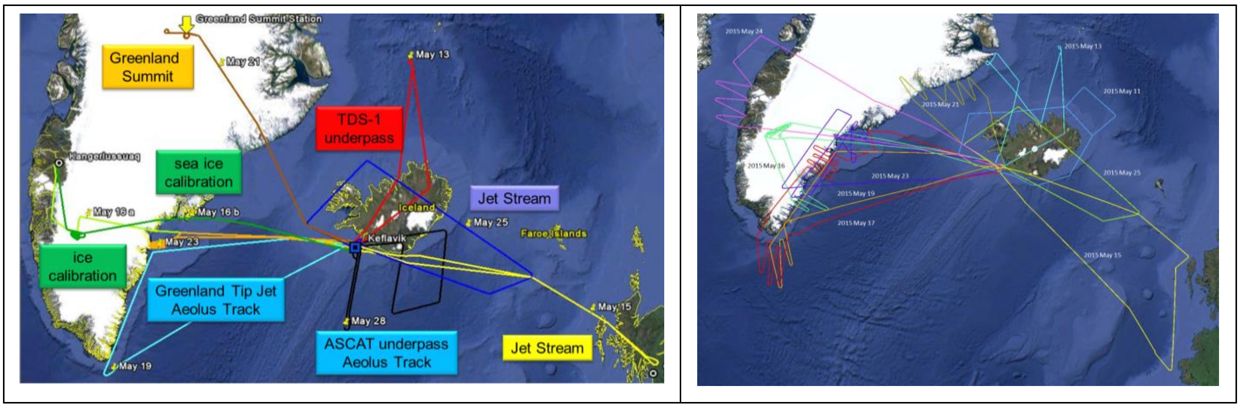

Figure 1. Flight tracks of the DLR Falcon from Keflavik, Iceland in May 2015 with the corresponding objective of the flight (left) and the track of the NASA DC-8 (right).

A number of 7 coordinated flights could be achieved. As the endurance of the Falcon aircraft is limited to about 4 hours, the DC-8 could fly more extended tracks up to 8 hours. A total of 101 dropsondes were deployed from the DC-8 measuring profiles of the horizontal wind vector, pressure, temperature and humidity. With a coordinated flight pattern the DC-8 could provide valuable information for the A2D calibration in nadir-viewing geometry with additional wind, temperature and pressures soundings. One flight of the DLR Falcon was targeted towards the Greenland summit with overpasses of the ground-based wind lidar.

3. Investigation of gravity waves by an airborne coherent Doppler Wind Lidar

In order to investigate the life cycle of GWs from their excitation towards propagation and dissipation, DLR's Institute of Atmospheric Physics recently initiated/participated in 3 airborne campaigns namely the GW-LCYCLE I campaign (Kiruna, Sweden, December 2013), the DEEPWAVE campaign (Christchurch, New Zealand, June/July 2014) [6], and the GW-LCYCLE II campaign (Kiruna, Sweden, January/February 2016). In the frame work of these campaigns, combined ground-based and airborne observations were conducted over northern Scandinavia and southern New Zealand, respectively, where both regions in winter-time represent distinguished conditions for the generation of mountain waves which are able to propagate up to the mesosphere.

One key-instrument was DLR's airborne 2 µm DWL which was operated from the Falcon. In order to characterize mountain waves, both horizontal and vertical wind measurements with high horizontal and vertical resolution and a low statistical uncertainty of several 10 cm/s are desired, where all of these goals can be reached with the DWL. In particular, horizontal and vertical wind is retrieved from line-of-sight (LOS) wind measurements by applying the velocity-azimuth-display (VAD) technique or by steering the beam to Nadir direction leading to a horizontal resolution of about 7 km and 0.2 km, respectively. The vertical resolution is approximately 100 m.

Vertical wind measurements require an exact nadir-pointing of the laser beam which is challenging to achieve from a moving platform as an aircraft. Thus, small contributions of the horizontal wind component might contaminate the vertical wind measurement. For that reason, a method to correct for slight off-nadir pointing angles by exploiting ECMWF re-analysis wind data and the actual beam pointing direction is developed. As the validity of this correction method is depending on the validity of ECMWF data, the wind vector measurements of the lidar are first used for verification. A DWL measurement, the corresponding ECMWF wind data and the direct comparison of both is shown in Fig. 2. The correlation yields an r^2 of 0.85, and the linear fit a slope of 1.00 and an intercept of 0.01 m/s and thus clearly demonstrates the usability of the ECMWF data for correction purpose.

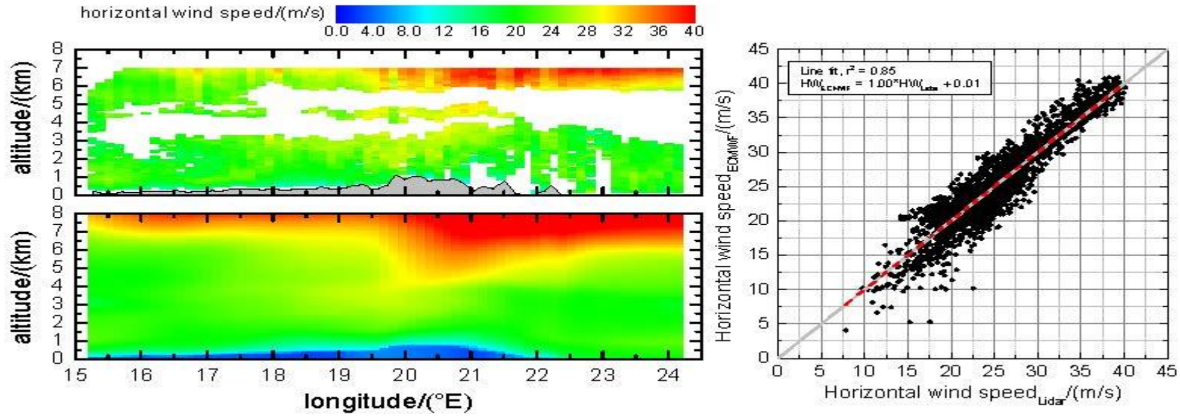

Figure 2. Left, top: Horizontal wind speed derived from lidar measurements. Left, bottom: Horizontal wind from ECMWF re-analysis data. Right: Lidar vs. ECMWF, line fit (red) and x=y line (gray).

Corrected vertical wind speeds of a research flight performed on 13. December 2013 during the GW-LCYCLE I campaign are shown in Fig. 3, top. Furthermore, the in-situ measured vertical wind from the aircraft is indicated at an altitude of 5.5 km. The data gap in-between is resulting from the pulse length of the laser which prevents to derive wind close to the aircraft. Anyway, the wind speed from the first lidar range gates and the in-situ measured wind speed show the same structure and thus additionally verify the reliability of the lidar data. From the measurement it is obvious that the vertical wind speed is varying around 0 m/s westwards of the Scandinavian mountains (up to 16.8° E). Going further eastwards, the excited gravity waves reach amplitudes of up to 3.5 m/s at the highest elevation at 19.3° E. By analyzing the wind speed in different altitudes (not shown) it can be shown that the amplitudes are decreasing with height. Thus, it is very likely that this particular wave was dissipating in the troposphere and did not reach higher altitudes. Further, the horizontal wavelength is determined by wavelet analysis (not shown) to be 10-20 km and thus, represents the orography structure.

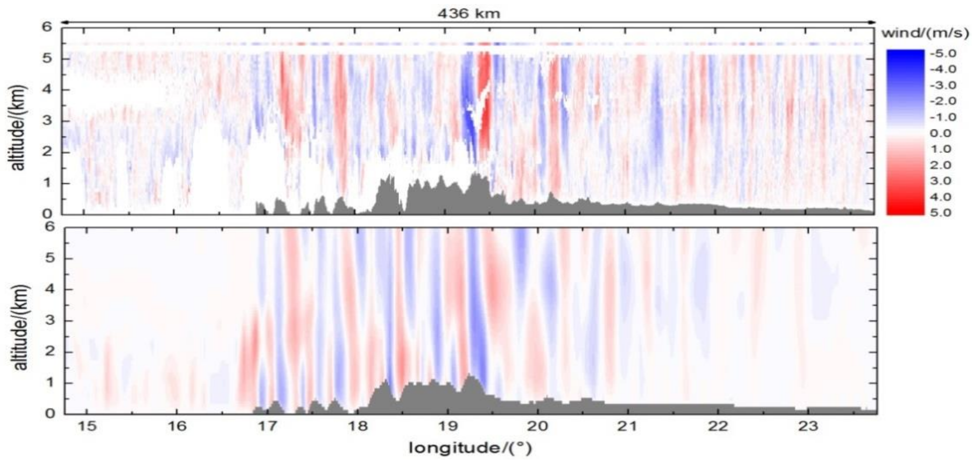

Figure 3. Top: Corrected vertical winds derived from lidar measurements performed on a research flight (13. December 2013). Bottom: Corresponding vertical wind speed from WRF-model.

A comparison with WRF model calculations (6 km and 2 km resolution, initialized with ECMWF data) as indicated in Fig 3, bottom shows quite good accordance with the measurement. The wave-pattern of the vertical wind is well represented. The amplitudes however are by a factor of 2 smaller and reach values of about 1.5 m/s. Explanations for that are under investigation.

4. Conclusion and Outlook

The extensive dataset from 4 wind lidars, dropsondes, ground-based instruments including the wind lidar on the Greenland Summit Station and numerical weather prediction model results are currently analyzed. The objectives of the WindVal campaign could be met and strategies for coordinated flights with 2 aircrafts were successfully proven. This forms the basis for future coordinated airborne validation campaigns for ADM-Aeolus after its launch.

Furthermore, 3 coordinated airborne campaigns were recently performed in order to investigate the life cycle of gravity waves. Both, the horizontal and the vertical wind measurements by DLR's coherent Doppler Wind Lidar are valuable for characterizing tropospheric gravity waves. In the future, it is foreseen to combine the lidar measurements with other airborne and ground based instrument data to characterize the whole life cycle of gravity waves from excitation to dissipation.

5. Acknowledgements

The WindVal was funded by NASA, ESA and DLR.

6. References

[1] European Space Agency ESA, "ADM-Aeolus Science Report", ESA SP-1311, pp. 121 (2008).

[2] Reitebuch, O., "The space-borne wind lidar mission ADM-Aeolus." in *Atmospheric Physics – Background, Methods, Trends.* U. Schumann ed. (Springer Series on Research Topics in Aerospace), pp. 815-827 (2012).

[3] Reitebuch O., C. Lemmerz, E. Nagel, U. Paffrath, Y. Durand, M. Endemann, F. Fabre, M. Chaloupy, "The Airborne Demonstrator for the Direct-Detection Doppler Wind Lidar ALADIN on ADM-Aeolus. Part I: Instrument Design and Comparison to Satellite Instrument.", J. Atmos. Ocean. Tech., **26**, 2501-2515 (2009).

[4] Paffrath U., C. Lemmerz, O. Reitebuch, B. Witschas, I. Nikolaus, V. Freudenthaler, "The Airborne Demonstrator for the Direct-Detection Doppler Wind Lidar ALADIN on ADM-Aeolus. Part II: Simulations and Rayleigh Receiver Radiometric Performance." J. Atmos. Ocean. Tech., **26**, 2516-2530 (2009).

[5] Reitebuch, O., C. Lemmerz, U. Marksteiner, S. Rahm, B. Witschas, "Airborne lidar observations supporting the ADM-Aeolus mission for global wind profiling." in Reviewed and Revised Papers of the 26th Int. Laser Radar Conference, Porto Heli, Greece, pp. S5O-01 (2012).

[6] Fritts, D. C., and Coauthors, 2015: The deep propagating gravity wave experiment (Deepwave): An airborne and ground-based exploration of gravity wave propagation and effects from their sources throughout the lower and middle atmosphere. *Bulletin of the American Meteorological Society*.

[7] Fritts, S., and M. J. Alexander, 2003: "Gravity wave dynamics and effects in the middle atmosphere". *Reviews of Geophysics*, **41** (1).

[8] Reitebuch, O., "Wind lidar for atmospheric research." in *Atmospheric Physics – Background, Methods, Trends.* U. Schumann ed. (Springer Series on Research Topics in Aerospace), pp. 487-507 (2012).

[9] Weissmann M., R. Busen, A. Dörnbrack, S. Rahm, O. Reitebuch, "Targeted Observations with an Airborne Wind Lidar." J. Atmos. Ocean. Tech., **22**, 1706-1719 (2005).

[10] Chouza F., O. Reitebuch, M. Jähn, S. Rahm, B. Weinzierl, "Vertical wind retrieved by airborne lidar and analysis of island induced gravity waves in combination with numerical models and in-situ particle measurements." Atmos. Chem. Phys., **16**, 4675-4692 (2016).

[11] Kavaya, M. J., J. Y. Beyon, G. J. Koch, M. Petros, P. J. Petzar, U. N. Singh, B. C. Trieu, J. Yu, "The Doppler Aerosol Wind (DAWN) Airborne, Wind-Profiling Coherent-Detection Lidar System: Overview and Preliminary Flight Results." J. Atmos. Oceanic Tech., **31**, 826-842 (2014).

[12] Gentry B., H. Chen, J. Cervantes, R. Machan, D. Reed, R. Cargo, C. Marx, and P. Jordan. "Airborne Testing of the TWiLiTE Direct Detection Doppler Lidar." Proc. 16th Coherent Laser Radar Conference, Long Beach, California, USA (2011).

[13] Yankee Environmental System: http://www.yesinc.com/news/research.html