AIRBORNE LIDAR OBSERVATIONS SUPPORTING THE ADM-AEOLUS MISSION FOR GLOBAL WIND PROFILING

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ABSTRACT

The Atmospheric Dynamics Mission ADM-Aeolus of ESA will be the first lidar mission to sense the global wind field from space. The instrument is based on a direct-detection Doppler lidar operating at 354.9 nm with two spectrometers for aerosol/cloud and molecular backscatter. In order to assess the performance of the Doppler lidar ALADIN on ADM-Aeolus and to optimize the retrieval algorithms with atmospheric signals, an airborne prototype – the ALADIN Airborne Demonstrator A2D – was developed. The A2D was the first airborne direct-detection Doppler lidar with its maiden flight on the DLR Falcon aircraft in 2005. Three airborne campaigns with a coherent-detection 2-µm wind lidar and the direct-detection wind lidar A2D were performed for pre-launch validation of Aeolus from 2007-2009. Furthermore, a unique experiment for resolving the Rayleigh-Brillouin spectral line shape in the atmosphere was accomplished in 2009 with the A2D from a mountain observatory at an altitude of 2650 m. Results of this experiment and the latest airborne campaign in the vicinity of Greenland and Iceland will be discussed.

1. THE ADM-AEOLUS MISSION

The European Space Agency ESA is currently implementing a Doppler wind lidar mission named Atmospheric Dynamics Mission ADM-Aeolus. It is considered as a technology demonstrator for future operational wind lidar missions. Aeolus will provide profiles of one component of the horizontal wind vector along the laser line-of-sight (LOS) from ground up to the lower stratosphere (20-30 km) with 0.25-2 km vertical resolution and a precision of 1-3 m/s depending on altitude [1,2]. A LOS wind profile will be obtained from a horizontal averaging length of 90 km along track without measurement gaps. This continuous horizontal averaging mode was recently implemented in contrast to an earlier approach with an averaging length over 50 km followed by a gap of 150 km.

The lidar ALADIN (Atmospheric LAser Doppler INstrument) is based on a direct-detection Doppler wind lidar (DWL) operating at 354.9 nm. The optical receiver consists of two spectrometers to determine the Doppler shift from the spectrally broad Rayleigh-Brillouin molecular backscatter and the spectrally narrow Mie backscatter from aerosols and cloud particles.

ALADIN combines new techniques, which were not implemented in a DWL before. The Rayleigh spectrometer uses the well-known double-edge technique with two Fabry-Perot interferometers, but in a new sequential implementation to increase the optical efficiency. The Mie spectrometer is based on a Fizeau interferometer, which are widely used as laser wavelength meters, but not within a DWL. Also the detectors are a novelty with two accumulation charge-coupled devices (ACCD´s) for the Rayleigh and Mie spectrometer signal. ALADIN will be the first European lidar and the first wind lidar in space.

2. PRE-LAUNCH CAMPAIGNS

A pre-launch campaign program for ADM-Aeolus was initiated, because of the novelty of the ALADIN instrument and the fact, that the satellite flight model instrument will be not illuminated with atmospheric signals before launch. Space industry will characterize the instrument thoroughly in a clean-room environment, but without the complexity of an atmospheric lidar signal. Furthermore, no direct-detection DWL was operated from an airborne platform in a downward looking geometry as from space, although, the techniques were pioneered more than 20 years ago.

In 2003, the development of an airborne instrument demonstrator – the ALADIN airborne demonstrator A2D – started for the validation of the ALADIN instrument and the related performance models [3]. A further objective was to obtain a dataset of atmospheric observations with an ALADIN type instrument from various atmospheric scenes (e.g. clear air, different cloud types or aerosol loadings, surface returns) to test, validate and optimize the ground processing and related quality-control algorithms, as well as the calibration schemes for the space instruments [4, 5]. Two ground campaigns were performed at the Meteorological Observatory of the German Weather Service (DWD) in Lindenberg in 2006 and 2007 with a number of complementary lidar and radar instruments [6]. The end-to-end photon budget from the molecular backscatter of the atmosphere, transmitted through the Rayleigh spectrometer, and detected by the ACCD was validated by collocated measurements of backscatter and extinction coefficients from the aerosol lidar MULIS of University Munich with good agreement [7].

3. AIRBORNE WIND LIDAR INSTRUMENTS

The direct-detection wind lidar A2D and the coherent-detection 2-µm wind lidar were deployed on the DLR Falcon 20 aircraft for airborne campaigns in 2007, 2008, and 2009 (Fig. 1). The A2D is based on the ALADIN receiver and transmitter from the pre-development program of ESA [3] and is therefore representative of the satellite instrument. The principle, optical layout, and specifications are discussed in detail in [8] and more specifically for the frequency-stabilized, and –tripled Nd:YAG laser in [9].

Figure 1. Photo of the direct-detection wind lidar A2D and the coherent-detection 2-µm DWL inside the DLR Falcon.

The 2-µm DWL was a major contributor to a number of atmospheric-science related airborne campaigns during the last 10 years. It was validated against wind measurements from dropsondes [10] and targeted airborne observations were assimilated into global numerical models for impact studies [11, 12, 13]. Thus, the 2-µm DWL provided a reference for the comparison with A2D wind measurements. Both lidars were installed above two bottom fuselage windows with a separation of only 50 cm. Therefore, both DWL´s pointed essentially in the same atmospheric volume with fixed off-nadir angle of 20° perpendicular to the aircraft roll axis. While the A2D provides only the wind speed component in LOS direction, as the satellite ALADIN instrument, the 2-µm DWL was operated alternately with fixed LOS direction and with conical scanning for horizontal wind vector measurements.

4. AIRBORNE CAMPAIGN RESULTS

One of the objectives of the airborne campaigns was related to the study of the sea surface reflectance in the UV spectral region for different incidence angles. Most of the sea surface reflectance observations were performed for visible or infrared wavelengths and nadir pointing, whereas ALADIN points with a 37.6° off-nadir angle during wind measurements and with 0° during calibration. Flights over the North Sea, Mediterranean Sea and the North Atlantic yielded the reflectance for different wind speeds up to 20 m/s. The reflectance was surprisingly high for low and medium wind speeds and incidence angles higher than 15°. This is due to an additional contribution of the ocean subsurface to the overall reflectance including specular and whitecap contributions [14].

In 2009, the A2D and the 2-µm DWL were deployed for an airborne campaign in the North Atlantic region with the Falcon aircraft based in Iceland. It is planned to calibrate the satellite instrument over ice and this concept was validated with the airborne prototype over the Greenland ice sheet. For calibration the satellite is rotated around its roll axis to point towards nadir in order to cancel out the horizontal wind contribution. The laser frequency is changed over the wind measurement range and the frequency of the atmospheric return is measured with both the Rayleigh and Mie spectrometer. The derived parameters from the calibrations are needed for the wind retrieval

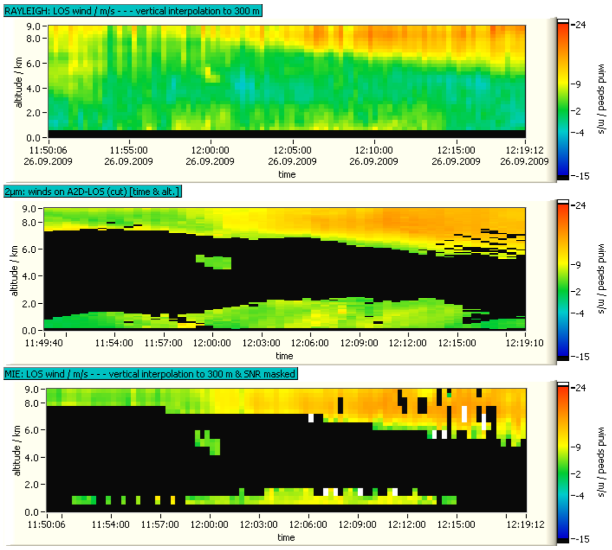

Figure 2. Airborne wind lidar observations along the east coast of Greenland on September 26, 2009 from the Rayleigh (top) and Mie spectrometer (bottom) of the A2D and the 2-µm DWL (middle) of the LOS wind speed; black/white colors indicate non-valid winds after quality-control; length of the flight track is 368 km.

An example of a LOS wind measurements of the 2-µm DWL and the A2D under 20° off-nadir angle along a 30 minutes flight track (corresponding to 368 km) along the east coast of Greenland is shown in Fig. 2 [15]. Strong winds are present in the jet-stream region between 6 and 9 km in the second half of the flight track. Due to the absence of thick clouds in a clean atmosphere, solely the Rayleigh spectrometer of the A2D, sensitive to molecular backscatter, is able to provide full vertical wind profiles. Close to the sea surface a distinctive region of up to 12 m/s is related to a katabatic flow from the Greenland ice sheet. Both the A2D Rayleigh and Mie winds are in good correspondence to the 2-µm DWL observations and a statistical comparison between A2D and 2-µm winds yields standard deviations of 1.9 m/s (Rayleigh) and 1.2 m/s (Mie), correlation coefficients r of 0.85 (Rayleigh) and 0.95 (Mie) and systematic differences below 1 m/s [15].

5. RAYLEIGH-BRILLOUIN LINE SHAPE MEASUREMENTS IN THE ATMOSPHERE

The accuracy of the wind retrieval using the double edge detection technique is depending on the exact knowledge of the spectral distribution of the backscattered light from molecules. The spectral distribution is originating from the Doppler shift caused by density fluctuations due to the thermal motion of the molecules (at constant pressure) and pressure fluctuations (at constant entropy), both described by the Rayleigh-Brillouin line shape. A pure Gaussian approximation of the line shape would cause a systematic error in the wind retrieval [16]. The most appropriate line shape model for atmospheric lidar applications is the Tenti S6 model [17], which was recently validated in air with a laboratory setup [18]. The usage of the Tenti S6 model for air was disputable, because it was derived and validated for molecular gases of single species and not for a mixture of several molecules as in air. A parameterization of the Tenti S6 model for relevant atmospheric temperature and pressures was derived by Witschas [19], which eases the implementation of the Rayleigh-Brillouin line shape for lidar simulations and retrievals.

Despite various measurements of the Rayleigh-Brillouin line shape in laboratory setups, no proof or validation was undertaken in the atmosphere with in backscattering geometry with scattering angle of 180°. Therefore, we investigated the line shape of molecular scattered light in the atmosphere from the mountain observatory “Schneefernerhaus”, located 300 m below the summit of Germany’s highest mountain – the Zugspitze (2962 m) in January and February 2009. The A2D lidar allowed spectrally highly resolved measurements by scanning the laser wavelength with a resolution of 20 fm (50 MHz) over 240 spectral positions of the Rayleigh-Brillouin line shape. The lidar beam was pointed horizontally to allow integration along almost constant pressure and temperature levels. The location of the mountain observatory was chosen, because the altitude of 2650 m enabled almost pure molecular backscatter observations above the atmospheric boundary layer during the winter months. Furthermore, the pressure of 700 hPa to 730 hPa is still large enough to exhibit a remarkable influence of Brillouin scattering on the line shape, which is originating from pressure fluctuations.

The fingerprint of Brillouin scattering on the spectral line shape could be clearly identified from the lidar observations over a frequency range of 12 GHz (Fig. 3). To our knowledge, this is the first experimental measurement of the spectrally-resolved Rayleigh-Brillouin line shape in the atmosphere. These measurements confirmed the currently used line shape model in the retrieval algorithms for the lidar instruments on ADM-Aeolus and EarthCARE.

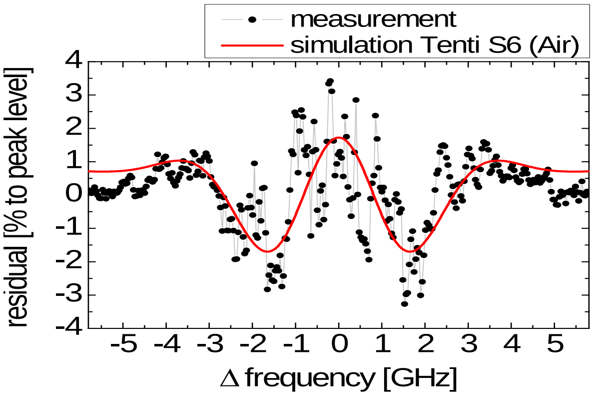

Figure 3. Fingerprint of the Rayleigh-Brillouin line shape from Tenti S6 model (red line) and horizontal lidar observations with the A2D (black dots).

6. SUMMARY

A direct-detection wind lidar – the ALADIN airborne demonstrator A2D – and a coherent-detection 2-µm wind lidar were deployed on the DLR Falcon aircraft from 2007-2009 for pre-launch validation campaigns to support the ADM-Aeolus satellite mission. More than 100 findings relevant for the satellite instrument on-ground testing, calibration, validation and processing algorithms were derived. A more fundamental issue related to the spectral line shape from Rayleigh-Brillouin scattering was addressed by an experiment from a mountain observatory. For the first time the Rayleigh-Brillouin line shape was resolved in the atmosphere by horizontal lidar observations. In contrast to space industry, which follows an engineering focussed approach, the validation campaign program by DLR was also motivated by scientific curiosity. This revealed some unexpected instrumental characteristics and behaviours, which were observed with real atmospheric signals. Thus, the pre-launch validation program with the airborne prototype significantly reduced some of the risks in developing a novel space-borne instrument.

This shows the importance of validating novel space-lidar instruments with real atmospheric signal before launch, preferably from an airborne platform with the same downward looking geometry as from space.

ACKNOWLEDGMENTS

Funding for the development of the ALADIN Airborne Demonstrator A2D and the airborne campaigns was provided by ESA and DLR.

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