PRE-LAUNCH VALIDATION OF ADM-AEOLUS WITH AN AIRBORNE DIRECT-DETECTION WIND LIDAR

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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. It is based on a direct-detection Doppler lidar operating at 355 nm with two interferometers for aerosol/cloud and molecular backscatter. In order to assess the radiometric and wind measurement performance of the Doppler lidar ALADIN on ADM-Aeolus, an airborne version – the ALADIN Airborne Demonstrator A2D – was developed. The A2D is the first airborne direct-detection Doppler lidar worldwide. The A2D receiver and laser transmitter performance characterization will be presented. Findings from two ground campaigns at the Observatory Lindenberg of German Weather Service in 2006 and 2007 using a wide variety of collocated observations will be discussed. The first results of an airborne campaign with the A2D and a coherent 2-µm wind lidar aboard the same aircraft will be shown.

1. ADM-AEOLUS

In 1999 the European Space Agency ESA decided to establish a Doppler wind lidar mission named Atmospheric Dynamics Mission ADM-Aeolus. The mission provides profiles of one component of the horizontal wind vector from ground up to the lower stratosphere (20-30 km) with 0.5-2 km vertical resolution and a precision of 1-3 m/s depending on height above ground. A line-of-sight LOS wind profile will be obtained every 200 km with a horizontal averaging length of 50 km [1, 2].

The ADM-Aeolus payload ALADIN (Atmospheric LAser Doppler INstrument) is based on a direct-detection Doppler lidar operating at 355 nm. The receiver consists of two spectrometers to determine the Doppler shift from the broadband Rayleigh molecular backscatter and the narrowband Mie backscatter from aerosols and clouds. The Rayleigh spectrometer uses the double-edge technique with a sequential Fabry-Perot interferometer, while the Mie spectrometer is based on a Fizeau interferometer. ALADIN will be the first wind lidar and also the first High-Spectral-Resolution-Lidar HSRL in space [3], as the molecular and the aerosol backscatter will be measured in two separate spectrometers.

2. PRE-LAUNCH CAMPAIGN OBEJECTIVES

An extensive pre-launch campaign program for ADM-Aeolus was established taking into account that:

- The satellite instrument will be tested and characterized on ground in a clean-room environment, but without illuminating it with atmospheric signals.
- Direct-detection Doppler lidars were validated in the past from the ground, but no direct-detection Doppler lidar was operated from an airborne platform in a downward looking geometry as from space.
- ALADIN combines new techniques, which were not implemented in a wind lidar before, like a novel combination of the molecular and aerosol receiver, the use of a Fizeau interferometer and Accumulation Charge Coupled Device ACCD as detectors.

In 2003 it was decided to start the development of an airborne instrument demonstrator for the validation of the ALADIN instrument and performance models from ground and from an airborne platform [4, 5]. The second 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 [6, 7].

3. ALADIN AIRBORNE DEMONSTRATOR

An airborne instrument version – called the ALADIN Airborne Demonstrator A2D – was developed by EADS-Astrium and DLR from 2003 to 2007. The core of the A2D is based on the ALADIN receiver and transmitter from the pre-development program of ESA [8, 9], and is therefore representative of the actual satellite instrument (Fig. 1).

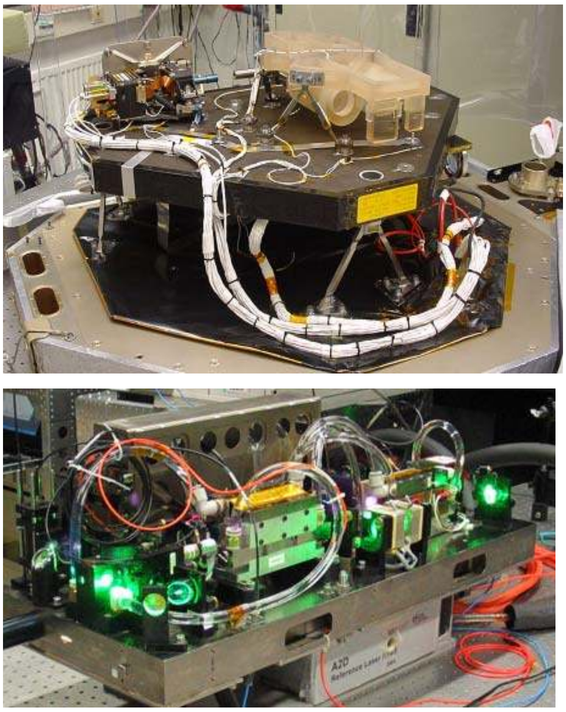

Figure 1. The ALADIN airborne demonstrator A2D receiver optical bench with Fizeau interferometer and ACCD detector (top) and laser transmitter (bottom).

Main differences of the A2D to the satellite instrument are the telescope, the transmit/receive optics and the laser transmitter implementation. A Cassegrain telescope with Ø 0.2 m is used for the receive path with a co-axial but separate laser transmit path, whereas a Ø 1.5 m telescope in a transceiver configuration is used for the satellite instrument. The airborne front optics include an electro-optical modulator for suppression of the near-field signal, a CCD camera for co-alignment of the transmit-receive path and a fiber coupling unit for the internal reference signal. The Mie and Rayleigh spectrometer, the ACCD and the detection electronics differ only in minor details in the airborne demonstrator and the satellite instrument. An end-to-end simulator was developed for the A2D including the retrieval algorithms to assess the radiometric and wind measurement performance [10]. An optical simulation model of the A2D using ZEMAX including all 60 optical elements is used to study the alignment sensitivity of the instrument.

The A2D laser transmitter consists of a frequency-tripled, diode-pumped, pulsed Nd:YAG laser with an output energy of 60-70 mJ at 355 nm at a pulse repetition frequency of 50 Hz. The master oscillator stage of the laser uses injection seeding from a reference laser to achieve the required frequency stability of better than 4 MHz at 355 nm. This corresponds to 1.3 MHz at the Nd:YAG fundamental wavelength of 1.06 µm and was verified in 2005 with a heterodyne method [11]. In addition the laser transmitter must be tunable in frequency over a large spectral range of ±6 GHz to calibrate the spectral response of the two interferometers.

First atmospheric signals could be obtained during test flights with the A2D in October 2005, but it was not possible to operate the laser single-frequency and seeded due to the aircraft vibrations. The laser oscillator was mechanically modified, and the active cavity control technique for the master oscillator was changed from pulse-built-up-time minimization to ramp-fire. Excellent results of single-shot frequency jitter of better 500 kHz at 1.06 µm were obtained during flights in April 2007 even during high aircraft vibration loads [12].

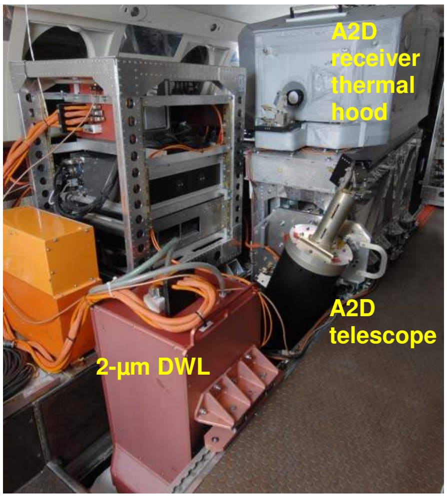

Figure 2. The ALADIN airborne demonstrator A2D and the 2-µm Doppler Wind Lidar DWL integrated in the DLR Falcon 20 aircraft during the first airborne campaign in November 2007.

4. RESULTS FROM GROUND AND AIRBORNE CAMPAIGNS

Ground campaigns at the Richard-Aßmann-Observatory of the German Weather Service DWD in Lindenberg were performed in October 2006 and July 2007. The reference instruments for the wind validation were a 482 MHz windprofiler radar WPR [13], the DLR 2-µm coherent Doppler wind lidar DWL (October 2006) [14] and radiosondes, which were launched up to 6 times per day. In order to characterize the atmospheric aerosol backscatter and extinction, the 355 nm DWD Raman lidar RAMSES [15], the University of Munich three-wavelength aerosol lidar MULIS [16], and a sun-photometer were operated. A cloud-profiling radar at 35.5 GHz measured cloud reflectivity (and thus cloud boundaries), cloud vertical velocity and linear depolarization. Due to its variety of operational remote sensing instruments and the orography of the site with relatively flat terrain, the DWD observatory Lindenberg is ideally suited for wind profile validation campaigns. The second ground campaign in July 2007 provided a comprehensive dataset of nearly 300 hours of A2D observations during different atmospheric conditions (clear air, low and high winds, broken low-level clouds, mid-level clouds, cirrus clouds, stratiform clouds) [17].

After test flights in October 2005 and April 2007, a first airborne campaign with 5 flights was performed in November 2007. The A2D and the DLR 2-µm coherent Doppler wind lidar were installed in the DLR Falcon 20 aircraft above the two bottom fuselage windows with a separation of only 50 cm. Both lidars were operated with a fixed line-of-sight pointing direction perpendicular to the aircraft axis. Flights tracks over the DWD observatory Lindenberg, and the multi-wavelength lidar of IFT Leipzig were chosen for comparison, and above the Alps and the Baltic and Mediterranean Sea to study the surface return.

Two exemplary results from the ground campaign are shortly discussed below.

4.1 Radiometric performance

A major objective for the ground campaign was the assessment of the radiometric performance models of the ALADIN instrument. Figure 3 shows the result of A2D measured signal intensity of the Rayleigh spectrometer during successive days, compared to the expected signal intensity from an end-to-end simulation. Simulated intensities were obtained using measured laser parameters (energy, divergence), measured receiver transmission parameters, modeled spectrometer spectral response and radiosonde temperature profiles to determine Rayleigh backscatter coefficient and spectral shape. It can be concluded that the simulated compares to the measured profile within a factor of 1-2.

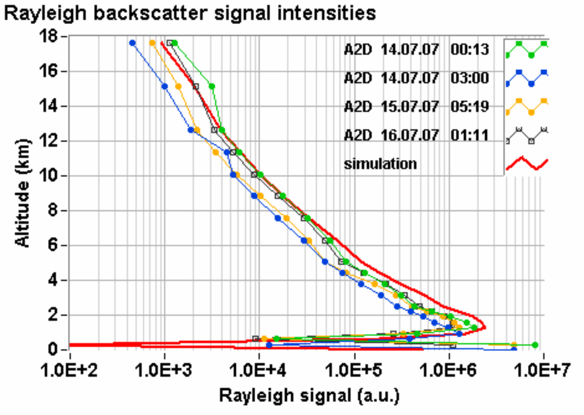

Figure 3. Measured signal intensity profiles (green, blue, yellow, black with symbol) of the A2D Rayleigh spectrometer compared to end-to-end simulations (red) to assess the radiometric performance.

4.2 Wind measurement performance

A2D line-of-sight wind profile observations were obtained pointing 15° off zenith and co-aligned to one of the windprofiler radar beams (Fig. 4). Observations could be obtained for clear-air conditions up to 12 km with a random error below 2 m/s. A systematic error for A2D observations was present below 3 km due to the range-dependency of the illumination of the Fabry-Perot interferometer in the telescope near field, which is not relevant for the satellite instrument.

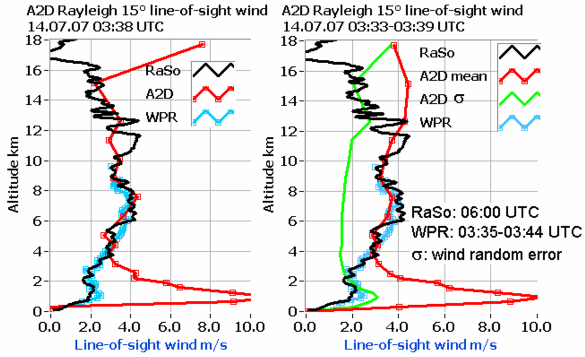

Figure 4. LOS wind profile from windprofiler radar WPR (blue), radiosonde RaSo (black) and from A2D (red) averaged over 14 s (left) and 6 minutes (right) including standard deviation σ of A2D observations during 6 minutes (green, right).

5. SUMMARY

The worldwide first airborne direct-detection Doppler lidar – the ALADIN airborne demonstrator A2D – was developed to support the ADM-Aeolus satellite mission. Ground and airborne campaigns including a coherent 2-µm wind lidar aboard the same aircraft were performed in 2006 and 2007. New findings relevant for the satellite instrument on-ground testing, calibration, validation and processing algorithms were derived.

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REFERENCES

[1] Stoffelen A., J. Pailleux, E. Källen, J. M. Vaughan, L. Isaksen, P. Flamant, W. Wergen, E. Andersson, H. Schyberg, A. Culoma, R. Meynart, M. Endemann, P. Ingmann, 2005: The Atmospheric Dynamics Mission for global wind field measurement. *Bull. Am. Meteorol. Soc.*, **86**, pp. 73-87.

[2] European Space Agency ESA, 2008: ADM-Aeolus Science Report, *ESA SP-1311*

[3] Ansmann A., U. Wandinger, O. Le Rille, D. Lajas, A. G. Straume, 2007: Particle backscatter and extinction profiling with the spaceborne high-spectral-resolution Doppler lidar ALADIN: methodology and simulations. *Appl. Opt.*, **46**, pp. 6606-6622.

[4] Reitebuch O., E. Chinal, A. Dabas, Y. Durand, M. Endemann, P. H. Flamant, R. Meynart, D. Morancais, U. Paffrath, G. Poberaj, 2003: Ground and airborne Doppler lidar campaigns for Atmospheric Dynamics Mission ADM. *Proc. 6th. Int. Symp. Tropospheric Profiling, Leipzig*, pp. 432-434.

[5] Reitebuch O., E. Chinal, Y. Durand, M. Endemann, R. Meynart, D. Morancais, U. Paffrath, 2004: Development of an airborne demonstrator for ADM-Aeolus and campaign activities. *Reviewed and Revised Papers 22nd Int. Laser Radar Conference, Matera, Italy, ESA SP-561,* pp. 1007-1010.

[6] Tan D., E. Andersson., J. Kloe, G.-J. Marseille, A. Stoffelen, P. Poli, M.-L. Denneulin, A. Dabas, D. Huber, O. Reitebuch, P. Flamant, O. Le Rille, H. Nett, 2008: The ADM-Aeolus wind retrieval algorithms. *Tellus A*, **60**, pp. 191-205.

[7] Reitebuch O., U. Paffrath, D. Huber, I. Leike, (2006): Algorithm Theoretical Baseline Document ATBD: ADM-Aeolus Level 1B Products, AE-RP-DLR-L1B-001, issue 3.0, 62 p.

[8] Durand Y., R. Meynart, M. Endemann, E. Chinal, D. Morancais, T. Schröder, O. Reitebuch, 2005: Manufacturing of an airborne demonstrator of ALADIN, the direct detection Doppler wind lidar for ADM/Aeolus. *Proc. SPIE Europe Int. Symposium Remote Sensing*, *Bruges, Belgium,* **5984**, pp. 5984-01.

[9] Durand Y., E. Chinal, M. Endemann, R. Meynart, O. Reitebuch, R. Treichel, 2006: ALADIN Airborne Demonstrator: a Doppler Wind Lidar to prepare ESA´s Aeolus Explorer Mission. *Proc. SPIE Optics and Photonics, San Diego, USA*, **6296**, pp. 6291-1D.

[10] Paffrath U. 2006: Performance assessment of the Aeolus Doppler wind lidar prototype. *Dissertation Technische Universität München, Juni 2006, DLR Forschungsbericht 2006-12, ISSN 1434-8454,* 137 p.

[11] Schröder T., C. Lemmerz, O. Reitebuch, M. Wirth, C. Wührer, R. Treichel, 2007: Frequency jitter and spectral width of an injection-seeded Q-switched Nd:YAG laser for a Doppler wind lidar. *Appl. Phys. B,* **87**, pp. 437-444.

[12] Witschas B., (2007): Characterisation of beam profile and frequency stability of an injection-seeded Nd:YAG laser for a Doppler wind lidar system. *Master Thesis University of Applied Sciences Munich*, 102 p.

[13] Steinhagen H., J. Dibbern, D. Engelbart, U. Görsdorf, V. Lehmann, J. Neisser, J. Neuschaefer, 1998: Performance of the first European 482 MHz Wind Profiler Radar with RASS under operational conditions. *Meteorologische Zeitschrift,* **7**, pp. 248-261.

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

[15] Engelbart D., J. Reichardt, I. Mattis, U. Wandinger, V. Klein, A. Meister, B. Hilber, V. Jaenisch, 2006: RAMSES – German Meteorological Service Raman Lidar for Atmospheric Moisture Sensing. *Reviewed and Revised Papers 23rd Int. Laser Radar Conference, Nara, Japan,* pp. 7O-2.

[16] Matthias V., V. Freudenthaler, A. Amodeo, I. Balin, D. Baslis, J. Bösenberg, A. Chaikovsky, G. Chourdakis, A. Comeron, A. Delaval, F. de Tomasi, R. Eixmann, A. Hagard, L. Konguem, S. Kreipl, R. Matthey, V. Rizi, J. A. Rodrigues, U. Wandinger, X. Wang, 2004: Aerosol lidar intercomparison in the framework of the EARLINET project: 1. Instruments *Appl. Opt.*, **43**, pp. 961-976.

[17] Reitebuch O., S. Kox, 2007: ADM-Aeolus Campaigns Website: http://www.pa.op.dlr.de/aeolus/