

ESA'S WIND LIDAR MISSION AND ITS CONTRIBUTION TO NUMERICAL WEATHER PREDICTION

Anne Grete Straume-Lindner, Paul Ingmann and the Aeolus Missions Advisory Group¹

ESA-estec, PO Box 299, 2200 AG Noordwijk, The Netherlands

Abstract

The European Space Agency (ESA) is developing a direct detection Doppler Wind Lidar, Aeolus, for the measuring of wind and atmospheric backscatter profiles from space. Aeolus is the second Core Explorer mission in the ESA Earth Explorer Programme. The primary product of Aeolus will be horizontally projected line-of-sight wind profile observations. The mission will, however, also deliver so-called spin-off atmospheric backscatter and extinction products for aerosol and cloud monitoring. During the technical development of Aeolus lidar instrument, ALADIN, changes to the mission measurement strategy had to be implemented in order to meet the stringent user requirements on stability and measurement accuracy. This has led to changes in the spatial representativity of the data. As a result of these changes to the mission, new impact studies have been initiated to consolidate an optimized on-ground data processing and make best use of the Aeolus data in Numerical Weather Prediction (NWP) assimilation systems.

The Aeolus mission and the recent updates to its data products will be presented here together with first results from the NWP impact studies and results from campaigns with an airborne version of Aeolus.

BACKGROUND AND MOTIVATION

The European Space Agency's (ESA's) Living Planet Programme includes two types of complementary user driven missions: the research oriented Earth Explorer missions and the operational service oriented Earth Watch missions. Earth Explorer missions are divided into two classes, with Core missions being larger missions demonstrating the capabilities of new technologies addressing issues of wide scientific interest, and the Opportunity missions that are smaller in terms of cost to ESA. Both types of missions address the research objectives set out in the Living Planet Programme document (ESA, 1999), which describes the Agency's strategy for Earth Observation in the coming decades. This has been extended in the ESA Earth Observation Strategy document (ESA, 2006). All Earth Explorer missions are proposed, defined, evaluated and recommended by the scientific community.

ESA's second Earth Explorer Core mission, Aeolus, is a direct detection Doppler wind Lidar for the measuring of wind from space. The pulsed High Spectral Resolution Ultra Violet (UV) Lidar shall deliver horizontally projected single line-of-sight tropospheric and lower stratospheric wind profiles in clear and particle rich air (aerosol layers and transparent clouds) and down to the top of optically dense clouds. The measurements will be delivered near-real-time (NRT, within 3 hours) and quasi-real-time for the region close to the data downlink station (QRT, within 30 minutes), for direct processing and ingestion into operational numerical weather prediction (NWP) models. The motivation for the selection of the Aeolus mission was the need for more abundant direct wind profile measurements in the current Global Observing System (GOS), which is used e.g. by NWP models. In the current GOS, direct wind profile measurements are obtained from radiosondes, commercial aircraft ascends and descends and ground-based wind lidars and radars. The distribution of the measurements is, however, not homogenous, with most observations taken over land in the Northern Hemisphere. Winds can also be inferred from temperature soundings, which are abundant from satellites. However, the wind field can only be estimated from temperature measurements when

¹ A. Dabas / MétéoFrance, P. Flamant / IPSL, E. Källén / ECMWF, H. Körnich / MISU, D. Offiler / MetOffice, H. Schyberg / met.no, A. Stoffelen / KNMI, O. Reitebuch / DLR, M. Vaughan / Lidar & Optics Associates, W. Wergen, M. Hardesty / NOAA, L.P. Riishoygaard / JCSDA, J. Yoe / NOAA

the flow is in geostrophic balance, which means that only large-scale winds in the extra-tropics can be obtained. Air Motion Vectors also provide valuable wind observations from cloud and aerosol tracking. These measurements are, however, limited by the difficulty in performing accurate height-assignments. It is therefore expected that the Aeolus mission will largely contribute to the improvement of predictions of small-scales flows and forecasts in observation-sparse regions. The Aeolus mission and the recent updates to its measurement strategy and data processing will be presented here together with results from NWP impact studies using simulated Aeolus data and results from campaigns with the Aeolus airborne demonstrator (A2D).

THE AEOLUS WIND MISSION

Scientific motivation

The current lack of homogenous sampling of the 3-dimensional wind field in large parts of the tropics and over the major oceans leads to major difficulties both in the studying of key processes in coupled climate systems and in the further improvement of NWP. It has been shown that direct wind profile measurements over the oceans and in the tropics are essential for improvements in short-range forecasts of severe weather (Marseille *et al.*, 2008) and a correct representation of the dynamics in the tropics (Žagar, 2004). Also the WMO (2004) report emphasise that there is a need for more uniformly distributed wind profile measurements, in particular in the Tropical and Polar regions. In the 1980s, studies looked into which satellite-based remote sensing techniques are most suitable for global wind profiling, and it was demonstrated that an active optical system (lidar) could provide global measurements of the required accuracy (e.g. Menzies 1986, Baker *et al.* 1995). Recommendations from the scientific and NWP community therefore lead to the selection of the Aeolus space-based lidar as ESA's second Earth Explorer Core mission in 1999.

The primary aim of Aeolus is to provide global observations of vertical wind profiles from the surface through-out the troposphere and lower stratosphere.

Spin-off products from Aeolus will be optical properties profiles. Information on cloud/aerosol layers, optical densities, backscatter and extinction coefficients, lidar and scattering ratios can be obtained.

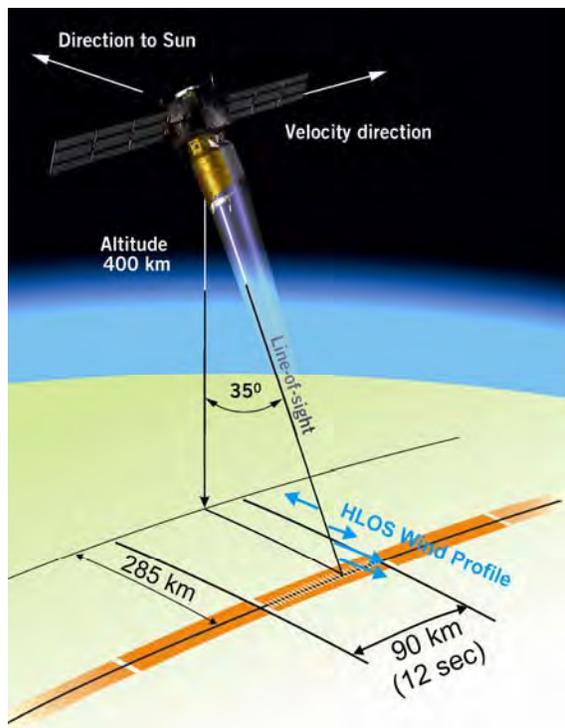


Figure 1: The Aeolus orbit, pointing and sampling characteristics

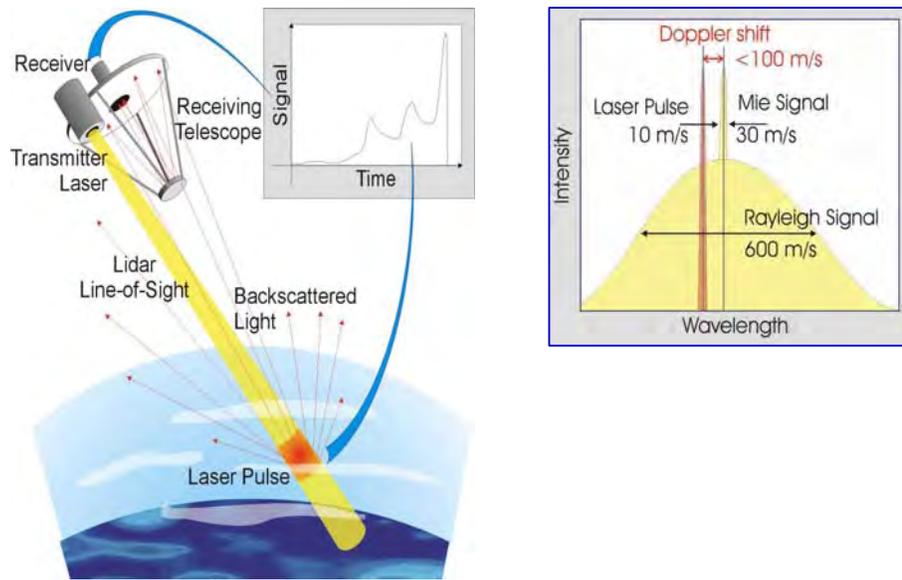


Figure 2: The Aeolus lidar measurement concept. The instruments emit and receive path is monostatic, but is shown skewed here for illustration purposes. The laser emits 355 nm frequency-narrow pulses at a frequency of 50 Hz, which are backscattered by molecules (Rayleigh scattering) and particles (Mie scattering) at various altitudes in the atmosphere (left panel). The movement of the molecules or particles along the laser line-of-sight cause a Doppler-shift of the emitted laser light, as illustrated in the right panel. The frequency shift is measured by the CCD detectors, allowing the estimation of the local wind speed. The backscattered laser light is also detected as a function of time, allowing the retrieval of wind profiles (left panel). The signals are time-averaged, resulting in layer averaged measurements from 250 m (near the surface) up to 2 km (in the stratosphere)

These spin-off products could become useful for aerosol assimilation by NWP models, acting e.g. as a gap-filler between the dedicated CALIPSO and EarthCARE aerosol missions. However, because the optical properties products will be retrieved from backscattered light at one wavelength only with no information about its polarization, the distinction of clouds and aerosols will only rely on the instruments high-spectral-resolution capability. Furthermore, the vertical and horizontal resolution of the optical products will be coarse as compared to dedicated aerosol lidars.

Instrument and measurement concept

Aeolus will embark a single instrument, namely the high spectral resolution Doppler wind lidar ALADIN (Atmospheric LAsER Doppler INstrument). ALADIN is a pulsed UV lidar (355 nm, 50 Hz, circularly polarized), operated in so-called continuous mode. This means that the instrument is measuring continuously along the track, as illustrated in Figure 1. Its high spectral resolution capability is the separate detection of the molecular (Rayleigh) and particle (Mie) backscattered signals in two channels. This makes it possible for Aeolus to deliver winds both in clear and (partly) cloudy conditions down to optically thick clouds. The height of the wind measurements in the atmosphere is calculated from the time it takes for the laser pulse to travel from the emitter to the backscatter altitude and back to the receive telescope (Figure 2). The backscatter signals are, furthermore, time-averaged resulting in layer-averaged measurements from 24 vertical bins per channel. The emitted laser pulse is frequency shifted and broadened by the motion of the scattering media before it re-enters the instrument and the instrument detectors. The frequency shift of the backscattered signal is proportional to the velocity of the scattering media along the instrument line-of-sight (LOS). The instrument is pointing perpendicular to the flight direction in order to remove any Doppler shift associated with the velocity of the spacecraft. After signal calibration and processing, the LOS wind speed can be retrieved and projected down to the horizontal (HLOS).

Aeolus will be launched in a sun-synchronous dawn-dusk orbit, with a descending equatorial crossing time at 6 am. A quasi-global coverage is achieved daily (by ~16 orbits, evenly distributed around the globe), and the orbit repeat cycle is 109 (7 days). A detailed description of the instrument design and operation can be found in (ESA, 2008).

Products

The main product from Aeolus is HLOS wind profile observations. The observations are constructed by the averaging of N measurements into 90 km horizontal averages. Each measurement is a 3 km horizontal average over the single shots, performed on-board the spacecraft. The observation averaging is done in order to achieve the necessary signal-to-noise ratio meeting the stringent wind accuracy requirements. The Aeolus Level 1b product contains calibrated HLOS measurements and observations, and will be delivered to NWP centres NRT/QRT. A stand-alone Level 1b to 2b processor is also made available, facilitating direct further processing and ingestion into the weather forecasting system. The Aeolus Level 1b to 2b processor performs a.o. quality control, temperature and pressure corrections and scene classification of the measurements within an observation. The Level 2b wind observations are then created by the averaging of individual measurements into separate profiles for clear air, broken clouds, cloud tops and above broken clouds as illustrated in Figure 3. ESA's operational Level 2b data centre at the European Centre for Medium-range Weather Forecasts (ECMWF) will deliver the operational Level 2b product with the frequency of its assimilation cycle (at the time of writing; every 12 hours). A further detailed description of the Aeolus wind profile retrievals and data delivery can be found in Tan *et al.* (2008).

The wind observation profiles are provided as layer-averaged winds from the surface up to 30 km for each of its two channels; the molecular (clear air) and particle (aerosol and cloud backscatter) channels. The instrument LOS is directed perpendicular to the flight direction (see Figure 1), which means that the zonal wind component can be deduced during most of the satellite's polar orbit by the above-mentioned simple horizontal projection. The vertical resolution of the layer-average winds vary from 0.25 to 2 km, and can be adapted through the orbit as a function of the under-laying topography and/or climate zone.

The required precision of the HLOS wind profile observations is 1 m/s in the planetary boundary layer and 2 m/s in the free atmosphere up to 20 km. 3-5 m/s is targeted in the lower stratosphere up to 30 km.

Aeolus spin-off products (Level 2a) include a.o. backscatter and extinction profiles, cloud and aerosol optical depths, cloud and aerosol layer top and base heights for optically thin clouds, with backscatter and extinction products. These are made available off-line, with a frequency similar to the L2b operational product. A detailed description of the Aeolus Level 2a processing and products is given in Flamant *et al.* (2008).

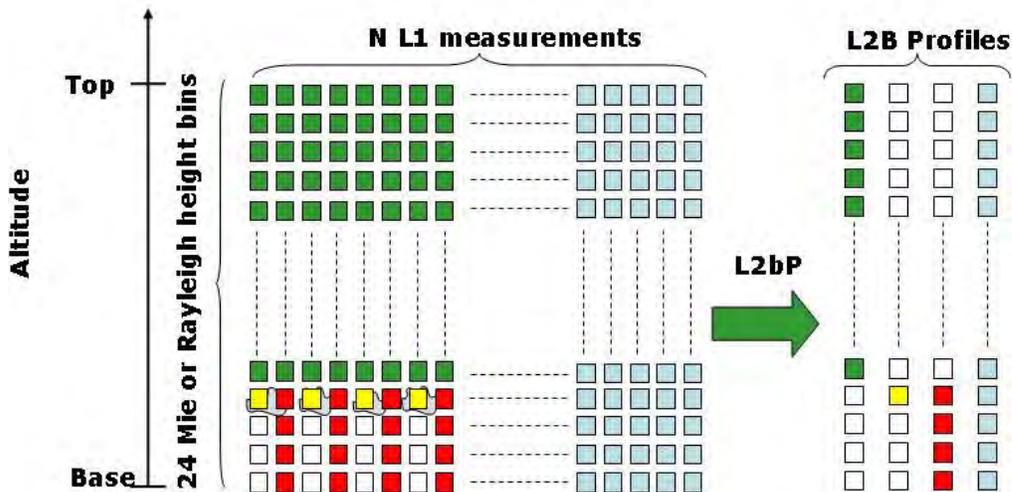


Figure 3: Schematic view of the Aeolus L2b wind observation processing. The processor classifies and average N measurements at 24 height levels (left) in an Aeolus observation into several partial or complete wind profiles. Grey: Broken cloud layer, White: No observations, Red, Between broken clouds, Blue: Cloud free, Green: Above broken clouds, Yellow: Cloud top returns. Base denotes the surface and Top denotes the maximum altitude of the height bins which can reach up to 30 km for the Rayleigh channel. After Tan *et al.*, 2008.

STRATEGIES FOR THE OPTIMIZATION OF THE AEOLUS OBSERVATIONS

During the technical development of the ALADIN laser, changes to the mission measurement strategy had to be implemented in order to meet the strict user requirements on stability and measurement accuracy. The former strategy was to operate the instrument in so-called pulsed burst mode, where the instrument was switched on for 50 km, once every 200 km. This operation mode allowed a pulse repetition frequency of 100 Hz resulting in observations with sufficiently high signal-to-noise ratio after measurement averaging over 50 km. The observations were spaced with 200 km, which assured an uncorrelated sampling scheme. The new strategy is to operate the instrument in so-called continuously pulsed mode, providing a continuous sampling along the orbit. Due to life-time issues, the pulse repetition frequency had to be reduced to 50 Hz, which has led to an increase of the necessary observation horizontal averaging length to 100 km.

This has led to changes in the spatial representativity of the data. As a result, new impact studies have been initiated to consolidate and optimize the on-ground data processing and make best use of the Aeolus data in NWP assimilation systems. Two study teams currently investigate in detail the role of NWP model background error correlations, measurement representativeness errors and an optimized measurement processing strategy to maximize mission impact. First results from one of these activities are described in Stoffelen *et al.* (2011). First results from the other study team at ECMWF show that the current operational version of the ECMWF model represents the atmospheric variability well, down to horizontal scales of about 100 km. Analysis of energy spectra showed that on scales smaller than 100 km the model does not maintain the expected energy level.

As mentioned above, the necessary horizontal averaging length for Aeolus wind profile observations is 100 km. The representativeness error of 100 km averaged wind observations is small, but their impact on NWP systems could potentially be smaller than e.g. point-measurements due to the lack of small-scale information.

Impact studies using an Ensemble Data Assimilation system (Tan *et al.*, 2007) will be performed at Stockholm University, using simulated Aeolus data made by the Royal Dutch Meteorological Institute (KNMI) using the so-called LIPAS simulator (Marseille *et al.*, 2003). Results from this investigation are expected to give recommendations for the Aeolus L2b observation horizontal and vertical averaging strategy to maximise NWP impact.

At ECMWF, a novel EDA-4DVar system will be run, replacing statistical climatologically described background error variances with flow-dependent estimates. Observation impact assessments will be performed by the use of conventional wind data types as well as simulated Aeolus data.

Recommendations for an optimal assimilation of Aeolus wind data shall be given.

AEOLUS AIRBORNE CAMPAIGNS

Extensive campaign activities have been performed to demonstrate the Aeolus measurement concept, using the ALADIN Airborne Demonstrator (A2D) (Reitebuch *et al.*, 2009). Two ground-based and three air-borne campaigns were performed, where A2D measurements were compared to independent measurements e.g. by radiosondes, ground-based and/or airborne lidars and ground-based radars. The last and most extensive of the airborne campaign was held in Iceland in September 2009. The campaign objective was to perform and optimize the in-flight response calibration, quantify systematic errors on the wind retrieval and to test the zero-wind calibration. Further objectives were to observe high wind speeds in combination with high vertical and possibly horizontal wind shear, to collect measurements of sea surface reflectance, to observe marine air-masses with low aerosol content and to perform observations of cloudiness and measurement coverage (Mie/Rayleigh) over centre of developing low-pressure systems. A preliminary comparison of wind measurements by the A2D and the accurate and well characterized 2 μm wind lidar on-board the DLR Falcon aircraft is shown in Figure 4. The figure shows that there is a very good overall agreement between the two measurement datasets, confirming the Aeolus measurement concept. So far, on the order of 100 recommendations for the Aeolus mission with respect to the instrument and algorithm development and testing have been made, based on the A2D campaign results. The measurements are, furthermore, the first atmospheric measurements worldwide with a Fizeau and Double Fabry-Perot UV lidar system.

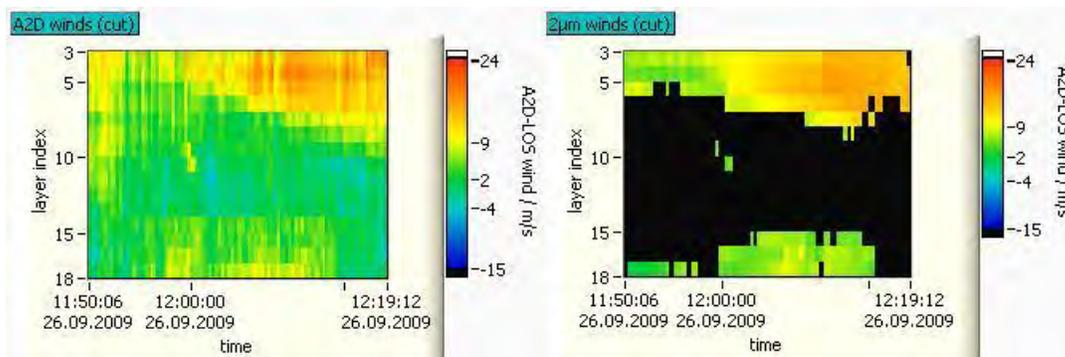


Figure 4: Preliminary comparisons of A2D and DLR 2 μ m wind lidar measurements on-board the Falcon, along the coast of Eastern Greenland, September 2009. With courtesy, U. Marksteiner and O. Reitebuch, DLR.

CONCLUSIONS

ESA is scheduled to launch its Aeolus Wind Lidar mission in the autumn of 2013, which will provide global wind profile observations in NRT for direct ingestion into NWP models. Recently, the mission measurement strategy had to be adapted in order to meet the strict user requirements on stability and measurement accuracy. The consequence was that the wind observation profiles are now 100 km horizontal averages with no spacing, as opposed to the earlier 50 km horizontal averages, spaced by 200 km. This results in a change in the spatial representativity of the data. On-going impact studies show that the observation representativeness error is now smaller, but the need to average the data over larger distances to achieve the same accuracy requirements leads to a loss of small-scale information. On the other hand, the laser now provides twice the amount of measurements per 200 km due to its continuous operation, which could compensate for the loss in horizontal resolution. This will be established after impact experiments using an Ensemble Data Assimilation system. Campaigns with the A2D instrument, which is an air-borne version of Aeolus, have demonstrated the measurement concept and delivered valuable recommendations for the instrument characterization, calibration and data processing.

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