ACTIVITIES IN SUPPORT OF THE DOPPLER WIND LIDAR PROFILING MISSION ADM-AEOLUS

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ABSTRACT

The European Space Agency 'Living Planet' programme (http://www.esa.int/export/esaLP/index.html) is ESA's programme for observing the Earth. The programme represents a flexible and user-friendly approach to the whole concept of Earth observation from space. Within this programme various types of missions are considered including research and demonstration missions.

Based on a proposal submitted in 1996 the Atmospheric Dynamics Mission ADM-Aeolus developed and was chosen as the second Earth Explorer Core mission for implementation in 1999. The ADM-Aeolus project entered Phase C/D in October 2003 with a scheduled launch of the satellite in 2007.

Complementing the technical activities with industry various supporting activities are being carried out, namely studies addressing scientific issues and campaign activities. At the last international winds workshop results of ground-based lidar campaigns and of wind statistics studies had been presented (Ingmann et al 2002).

Currently work is being performed on the contribution of ADM-Aeolus to tropical analyses and on the potential impact of line-of-sight (LOS) wind observations on model analyses and forecasts using data assimilation systems.

1. INTRODUCTION

The 'ESA Living Planet Programme' (http://www.esa.int/export/esaLP/index.html) is gaining momentum. Four Earth Explorer missions are currently being implemented, namely GOCE, CRYOSAT, ADM-Aeolus and SMOS. Information about the four missions can be found at the same URL. Another four missions have been recommended for either immediate implementation or detailed study in May 2003.

ADM-Aeolus had been selected in 1999 for getting implemented as the second Earth Explorer Core mission. In October 2003 the project entered Phase C/D with the signature of the development contract with industry. In addition to work performed on the technical side various activities are either on-going or being initiated at present, which will be subject of this document.

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The overall context of the mission had been in explained in some detail in earlier papers (e.g. Ingmann et al 2002) and will not be repeated here.

2. BACKGROUND

During the past 15 years the European Space Agency, ESA, has been evaluating the prospects for a space-borne Doppler Wind Lidar (DWL) for the measurement of the global wind field. Early concepts had been developed by the Doppler lidar working group (ESA 1989). These preparatory activities, including theoretical studies, technical developments and field campaigns, have been described in a “Report for Mission Selection” (ESA 1999). This report was presented to the European Earth Observation community at a selection meeting. Four candidate Earth observation missions were considered, and the Atmospheric Dynamics Mission for wind profile measurement was selected as the second of these Earth Explorer Core Missions to be implemented. It is now an approved mission of the European Space Agency with a target date for launch of 2007.

The primary aim of the Atmospheric Dynamics Mission (ADM-Aeolus) of the European Space Agency is to provide global observations of vertical wind profiles. Presently, knowledge of the 3-dimensional wind field over large parts of the tropics and major oceans is quite incomplete. This leads to major difficulties both in studying key processes in the coupled climate system and in further improvement of numerical forecast systems. Progress in climate modelling is intimately linked to progress in numerical weather prediction (NWP). The wind profile measurements provided by ADM-Aeolus are expected to lead to significant improvements in such atmospheric modelling and analysis. These advances will in turn enhance the long-term databases being created by NWP data assimilation systems to serve the climate research community. As such, the ADM-Aeolus promises to also provide data needed to address some of the key concerns of climate research including climate variability, validation and improvement of climate models, and process studies relevant to climate change.

Alike many other meteorological observations, the space-borne LOS wind component profiles by themselves seem at first glance to be of limited value, but in the context of atmospheric data assimilation systems they would in fact be an essential component of the GOS, just like radiosonde wind profiles today. For a mission intended to demonstrate the feasibility of a full-scale space-borne wind observing system to improve global atmospheric analyses, the requirements on data quality and vertical resolution are the most stringent and most important to achieve. Under this assumption, the density of profile observations is of lower priority amongst the requirements. However, the derivation of the coverage specification is supported by weather forecast impact experiments, which included the inputs of the conventional wind-profile network that is thin and irregular but of key importance. Moreover, the coverage specification is compatible with the World Meteorological Organisation WMO threshold requirements. The WMO recognises the prime need for wind profile data (WMO 2000) and has defined wind profile measurement requirements (e.g. WMO 2001).

Over data sparse areas the 2-3 m s^{-1} accuracy requirement is expected to be sufficient to provide a beneficial impact on meteorological analyses; the requirement is comparable with the typical first guess error. This requirement is significant as experience in meteorological data assimilation shows that observations with an accuracy poorer than the first guess often fail to have a significant beneficial impact on NWP. In summary, Table 1 provides an overview on the ADM-Aeolus requirements.

The concept of the mission is explained in Figure 1. A very high performance DWL will be accommodated on a satellite flying in a sun synchronous orbit, at an altitude of ~ 400 km and providing near-global coverage. The DWL is an active instrument which fires pulses of laser light towards the atmosphere along a Line-Of Sight (LOS). The space-borne lidar will emit a spectrally narrow laser pulse directed at a 35° slant angle towards the atmosphere. Laser light of wavelength 355 nm is scattered in the atmosphere by molecules (Rayleigh-Brillouin scattering) and by small aerosol and cloud particles (Mie scattering) moving with the wind. A very small fraction of such scattering is backscattered towards the spacecraft. The scattered light has a different frequency than the light that is emitted by the Laser because of the Doppler effect: Due to the scatterer’s relative movement in the direction of observation, a frequency shift occurs. Thus it allows determining mean wind component velocity profiles.

		PBL	Troposphere	Stratosphere
Vertical Domain	[km]	0-2	2-16	16-20
Vertical Resolution	[km]	0.5	1.0	2.0
Horizontal Domain		global		
Number of Profiles	[hour^{-1}]	> 100		
Profile Separation	[km]	> 200		
Horizontal Integration Length	[km]	50		
Horizontal Sub-sample Length	[km]	0.7 to 50		
Accuracy (HLOS Component)	[m/s]	1	2	3
Data Reliability	[%]	95		
Data Availability	[hour]	3		
Length of Observational Data Set	[yr]	3		

Table 1: ADM-Aeolus observational requirements.

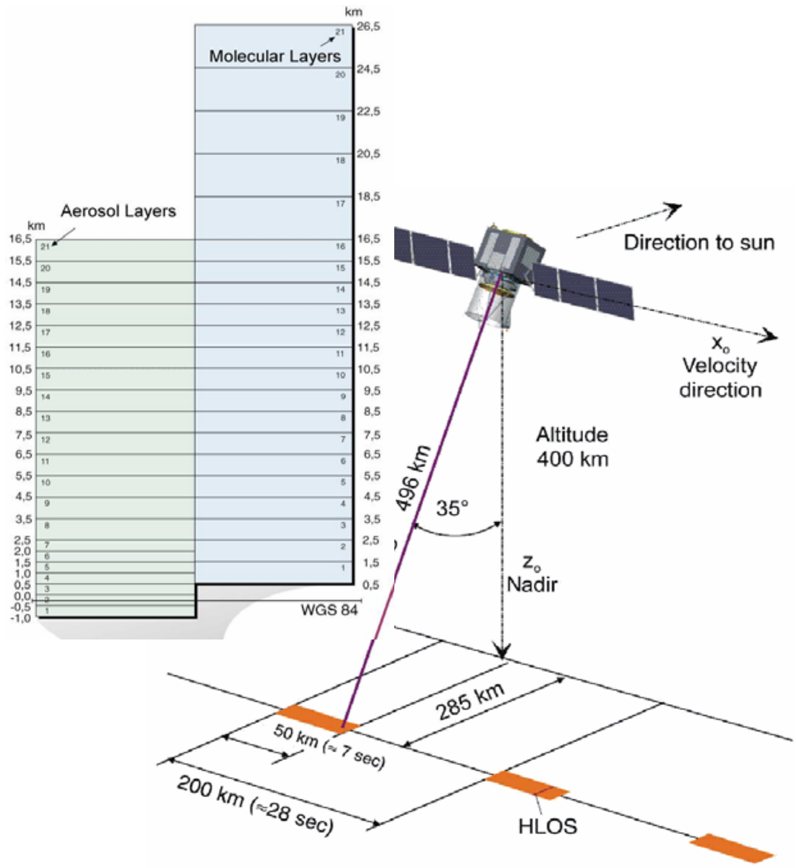

Figure 1: Doppler Wind Lidar principle and measurement geometry.

The lidar emits a laser pulse towards the atmosphere, then collects, samples and retrieves the frequency of the backscattered signal. The received signal frequency is Doppler-shifted from the emitted laser light due to the spacecraft motion, Earth rotation and wind velocity. The lidar measures the wind projection along the laser line-of-sight, using a slant angle versus nadir. Also shown is the mapping of atmospheric heights to layers measured by the detector. The vertical as well as the horizontal values can be programmed, providing observation flexibility.

The Doppler shift is determined from both, the Rayleigh and the Mie scattering, using independent receivers for each.

Though only the altitude range of 0 to 20 km had been required (cf Table 1) recent performance evaluations indicate that useful performances can also be expected up to 30 km and beyond. Figure 2 shows expected performances versus height.

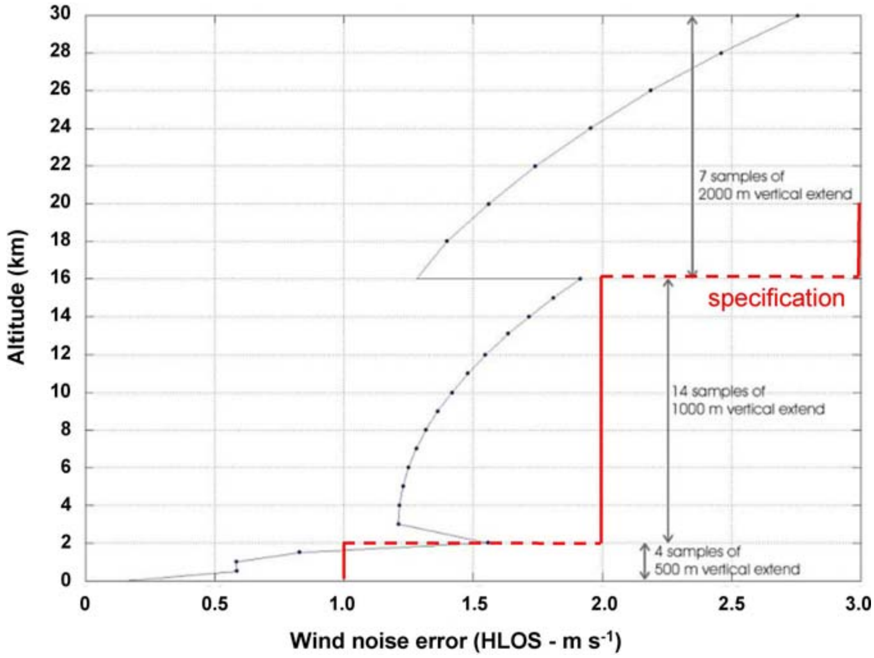

Figure 2: ADM-Aeolus performance estimates between surface and 30 km altitude. The red lines indicate specifications, cf Table1.

3. TECHNICAL CONCEPT

In early proposals dedicated to wind measurements from space NOAA and NASA considered CO_2 laser technology, with heterodyne detection and a conical scan at ~ 45º from nadir to sample the atmospheric wind field. This basic concept was proposed for e.g. the LAWS projects (Baker 1995). The CO_2 laser technique was considered as mature at that time but the necessary accuracy for LOS measurements resulted in demanding requirements for a large CO_2 laser system, a large scanning telescope and a lag angle compensation unit.

In parallel with these studies, ESA has been considering the feasibility of a space based Doppler wind lidar. These activities have resulted in the selection of a high performance Doppler wind lidar based on direct detection implementing interferometric techniques at the receiver level. This technique has been developed 30 years ago (Benedetti-Michelangeli et al. 1972) and used routinely since then at 532 nm (Chanin et al. 1989). For eye safety reason a UV wavelength is preferable. As a result, such a system, with pulsed laser operating at 355 nm wavelength would utilize both Rayleigh-Brillouin scattering from molecules and Mie scattering from thin cloud and aerosol particles.

The ADM laser source is based on a single mode, 150 mJ, 100 Hz pulse repetition frequency, diode pumped and frequency tripled (355 nm) Nd-YAG laser. A 1.5 m diameter Cassegrain afocal telescope is proposed as transceiver (for both transmitting and receiving). The full observation of 700 shots is taken over typically 7 seconds, followed by a quiet period of about 21 seconds. In this 7-second measurement period the satellite will have travelled approximately 50 km and thus the wind fields will have been effectively averaged over this distance in the propagation direction. The vertical height resolution is determined by techniques of time gating the return signal. Extensive studies of system performance by both scientific laboratories and industry in the framework of preparatory studies had been carried out (e.g. ESA 1999; Marseille and Stoffelen 2003). Overall system analysis, with budgeting for a wide range of potential errors sources, shows performance within the required specification. The ADM-Aeolus satellite (Figure 3) will have a mass of about 1200 kg and will require about 2.8 kW of power.

ADM-Aeolus will provide about 3,000 globally distributed wind profiles per day, above thick clouds or down to the surface in clear air at typically 200 km separation along the satellite track. The latter is compliant with synoptic analysis. Wind information in thin clouds or at the top of thick clouds is also attainable; information on other elements such as cloud and aerosols can be extracted as well. A near real-time delivery of data to the main NWP centres is anticipated.

In addition, since ADM-Aeolus is a high spectral resolution lidar the signal strengths in the Rayleigh and Mie channels can be used to derive secondary products like aerosol and cloud optical properties.

Figure 3: Artist view of ADM-Aeolus satellite with laser beam targeted at the Earth's atmosphere.

After the detailed design of the hardware, integration and testing of the major building blocks, as well as satellite and instrument integration and testing, the launch is planned to be in late 2007.

4. SCIENTIFIC ACTIVITIES

In the past activities had focused on confirming the basic assumptions for the mission, namely confirming that line-of-sight (LOS) winds are sufficient. Observational (system) simulator experiments (O[S]SE's) were performed. More recently, work has focused on particular events, e.g. high impact weather and on the preparation for an operational use of the data. In this context work has been carried out at the University of Stockholm and at the European Centre for Medium Range Weather Forecasts (ECMWF).

At Stockholm University the assimilation of equatorial waves by LOS wind observations has been investigated (Zagar 2004). The potential of LOS wind information from a space-borne Doppler wind lidar to reduce uncertainties in the analysis fields of equatorial waves has been assessed by comparing their impact to that of a single wind component, full wind field information and mass field data in three- and four-dimensional variational data assimilation.

The dynamical framework consists of non-linear shallow water equations solved in a spectral space and a background error term based on Eigen modes derived from linear equatorial wave theory. Based on observational evidence, the background error covariance matrix for the multivariate analysis contains equatorial Kelvin, Rossby, mixed Rossby-gravity and the lowest two modes of the westward propagating inertio-gravity waves. The same dynamical structures are utilized to simulate the observations. Results from the single observation experiments illustrate that the assimilation increments due to LOS wind information are more dependent on the background error term specification than is the full wind field information. This sensitivity is furthermore transferred to the balanced height field increments.

Identical twin assimilation experiments suggest that LOS wind observations have a capability of being valuable supplemental information to the existing satellite mass field measurements. Although the new wind information is incomplete, it can provide reliable analysis of tropical wave motions, when it is used together with the height data. A result showing the impact of LOS wind observations is shown in Figure 4.

A second study is looking into the expected benefits of wind profiles from the ADM-Aeolus mission in a data assimilation system

The main objectives of the study are:

- To analyse atmosphere penetration capabilities of real measurements based on LITE and ELITE campaigns in meteorologically sensitive regions and meteorological dynamical region indicators

- To investigate the treatment of simulated DWL observations in a data assimilation system

- To perform assimilation studies s with simulated wind profile observations.

Simulated Aeolus data have been assimilated in Analysis Ensemble experiments. The original technique (Fisher and Andersson, 2001) has been extended to permit the data impacts to be assessed. The novelty of the extended technique meant that calibration was required; this was achieved through radiosonde denial experiments in the analysis ensemble technique.

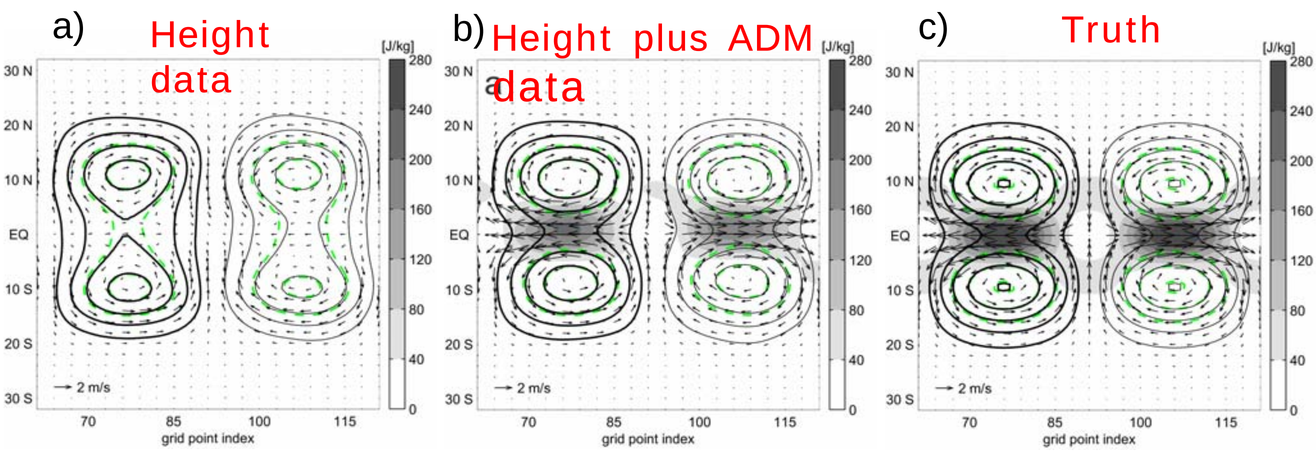

Figure 4: Here mass: using mass field (height, a) and mass plus wind field (LOS, b) for reconstructing the true (original) field, field alone (a), mass plus LOS wind field (b) and the original field ('truth') (c) are compared. The advantages of wind profile over mass field data in the tropics is demonstrated.

The ensemble approach has involved assimilation of simulated Aeolus Level-2B data in many 6-week assimilations with each ensemble member assimilating differently perturbed observations. The treatment of Level-2B data (calibrated wind profiles) developed in this study has proved robust in all cases, and provides a good foundation for the development of higher level products.

The new technique suggests that the main benefits from ADM-Aeolus for analysed wind fields will be found over ocean regions in both hemispheres and in the Tropics. These regions have been identified previously as priority areas for improvement. The advantages seen in analysed fields lead to benefits in forecast fields as well, throughout the depth of the troposphere.

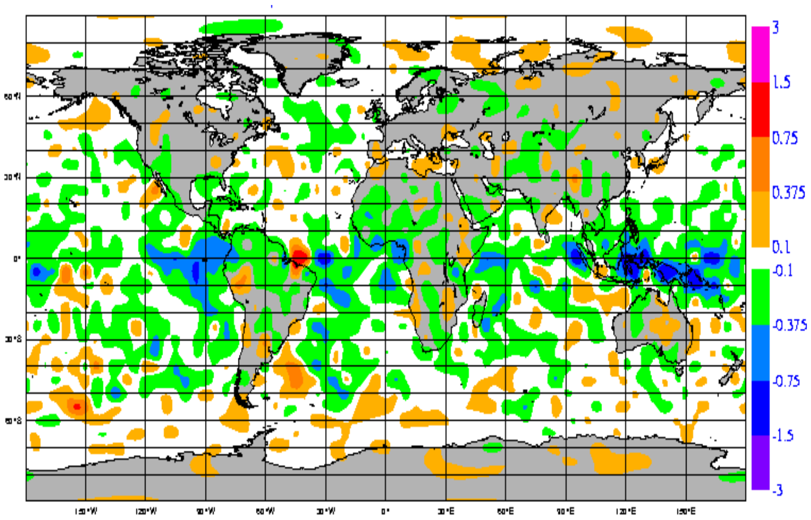

Figure 5: ADM-Aeolus impact on analysis ensemble spread at 200 hPa. Benefits are indicated by negative values in blue colours.

It is becoming apparent that the major issues for successful NWP exploitation of Aeolus data are a) the ability to produce high-quality Level-2B data in near real time, and b) good characterization of observation and background ("model first-guess") errors within the assimilation system.

It is noted that the work of (Zagar et al. 2004) contributes to (b) especially in the Tropics, and their comment on the need for an approach that combines tropical and mid-latitude dynamics and produces balanced increments globally. The impact for the tropics is shown in Figure 5 where the impact of ADM-Aeolus observations at 200 hPa is shown. The impact is largest at tropical latitudes.

In addition, work is progressing towards ground-based and airborne campaigns making use of a prototype ALADIN instrument. The latter are underway to obtain realistic atmospheric situations for the testing of the retrieval algorithms and to allow final selection of instrument parameters for optimised in-orbit measurement performance. Table 2 summarises the planned campaign activities (A2D stands for ADM-Aeolus demonstrator).

Campaign	**Location**	**Time**	**Instruments**
ADM-Aeolus Ground Campaign	Lindenberg DWD-MOL	May 2005	A2D within container (DLR) 2µm lidar within container (DLR) 482 MHz windprofiler radar (DWD) 35.5 GHz cloud radar (DWD) laser ceilometer (DWD) sun-photometer (DWD) 4 operational RASO/day + 10 additional (DWD) aerosol lidar 355 nm (MIM)
ADM-Aeolus Airborne Campaign 1	Overflights Lindenberg (and other sites)	March 2006	A2D and 2µm in DLR Falcon DWD-MOL instruments
ADM-Aeolus Airborne Campaign 2	TBD	Sept/Oct 2006	A2D and 2µm in DLR Falcon additional instruments, if linked to another campaign

Table 2: Planned ADM-Aeolus related campaign activities (MOL = Meteorological Observatory Lindenberg).

5. CONCLUSIONS

The Atmospheric Dynamics Mission, ADM-Aeolus, is currently being developed by the European Space Agency within its Living Planet Programme. The ADM-Aeolus will demonstrate the capability of a space-borne Doppler Wind Lidar to accurately measure wind profiles in the troposphere and the lower stratosphere (0-20 km). The Mission thus addresses one of the main identified deficiencies of the current Global Observing System. From the backscattered frequency-shifted laser light it will be possible to obtain about 3,000 globally distributed profiles of horizontal line-of-sight winds daily and with good vertical resolution. The accuracy of ADM winds, in most cloud-free regions and above thick clouds, is expected to be comparable to that of radiosonde wind measurements.

The ADM-Aeolus wind profiles will find wide application in NWP and climate studies, improving the accuracy of numerical weather forecasting, advancing our understanding of tropical dynamics and processes relevant to climate variability and climate modelling. With a target launch date in 2007, work has already been instigated preparing for the future real-time assimilation of ADM-Aeolus wind data into operational NWP models. The mid-latitude focus is on those regions where forecast performance is known to be particularly sensitive to the accuracy of initial conditions. In particular, a beneficial impact on the prediction of severe storm events is expected and further investigated. For the tropics the focus of current investigations is on defining the appropriate mass/wind relationships for effective assimilation of the ADM wind data. In an operational framework, assimilation of line of sight winds has been performed globally. The results show that the largest benefits from line of sight winds can be expected over the oceans and in the Tropics.

During its projected three-year lifetime the ADM-Aeolus will demonstrate the feasibility of global wind field measurement from space. Following a successful ADM, future operational missions may be built, fully exploiting the concept of space-borne Doppler Wind Lidars.

6. REFERENCES

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