STATUS OF THE DOPPLER WIND LIDAR PROFILING MISSION ADM-AEOLUS

Anne Grete Straume-Lindner, Paul Ingmann, Martin Endemann, and the members of the ADM-Aeolus MAG[1]

European Space Research and Technology Centre (ESA - ESTEC)
P.O. Box 299, NL-2200 AG Noordwijk, The Netherlands
e-mail: Anne.Straume@esa.int

Abstract

The Atmospheric Dynamics Mission ADM-Aeolus was chosen as the second Earth Explorer Core mission for implementation in 1999. ADM-Aeolus will be the first active remote sensing satellite to map global wind profiles for real-time use in numerical weather prediction. The ADM-Aeolus is expected to pave the way for future operational meteorological satellites dedicated to measuring the Earth's wind fields.

In October 2003 the ADM-Aeolus project entered Phase C/D, and the scheduled launch of the satellite is late 2008. Complementing the technical activities with industry, various supporting activities are carried out, namely studies addressing scientific issues and campaign activities. Currently the scientific studies are focussing on particular events, e.g. on high-impact weather, on the preparation for an operational use of the data, on the potential of the ADM-Aeolus additional aerosol and cloud products, and on the adaptation of ADM-Aeolus for full operational use.

INTRODUCTION

ESA has been dedicated to observing the Earth from space ever since the launch of its first meteorological mission Meteosat back in 1977. Following the success of this first mission, the subsequent series of Meteosat satellites, ERS-1, ERS-2 and Envisat have provided a wealth of invaluable data characterizing the Earth’s climate and changing environment. As a follow-up, ESA's Living Planet Programme (http://www.esa.int/export/esaLP/index.html) was created, comprising of two main components: a science and research element in the form of the Earth Explorer missions, and the Earth Watch element designed to facilitate the delivery of Earth Observation data for the eventual use in operational services. The Earth Explorer missions are designed to address critical and specific issues that have been raised by the science community, and at the same time demonstrating breakthrough technology in observing techniques.

Six Earth Explorer missions are currently being implemented within the ESA Living Planet Programme, namely GOCE, CRYOSAT-2, ADM-Aeolus, SMOS, Swarm, and EarthCARE. Information about the six missions can be found at the above mentioned URL. A new call for Earth Explorer Ideas was released on 15 March 2005. The 24 proposals that were received before the deadline on August 15 2005 have been evaluated, and six of them have been selected for a further 18 months study. The results from these studies will form the basis for the final selection of the next Earth Explorer mission. The 6 selected proposals are BIOMASS, TRAQ, PREMIER, FLEX, A-SCOPE, and CoReH2O.

The first European satellite-based wind lidar concepts were developed by the Doppler lidar working group (ESA, 1989). These preparatory activities, including theoretical studies, technical developments and field campaigns, are described in “Report for Mission Selection” (ESA, 1999). This report was presented to the European Earth Observation community at the Earth Explorer selection meeting, and in 1999 ADM-Aeolus was selected for implementation as the second Earth Explorer Core mission. The technical pre-development started in 2000, and with the signature of the development contract with industry in October 2003 the project entered Phase C/D. The critical design review was completed in September 2005. The launch is scheduled for autumn 2008.

Both scientific and campaign activities are being and will be performed in parallel to the technical development. Furthermore, the adaptation of ADM-Aeolus for full operational use is explored. Below, an overview of the ongoing scientific studies and campaign activities is given.

SCIENTIFIC MOTIVATION

The scientific motivation behind the Atmospheric Dynamics Mission (ADM-Aeolus) was reported during the previous winds workshop (Ingmann et al., 2004), and is further described by Stoffelen et al. (2005). Only a brief summary will be given here.

The primary aim of ADM-Aeolus is to provide global observations of vertical wind profiles from the troposphere and lower stratosphere. Presently, the sampling of the 3-dimensional wind field in large parts of the tropics and over the major oceans is far from sufficient in the global observation system (GOS). This leads to major difficulties both in the studying of key processes in the coupled climate system and in the further improving of numerical weather prediction (NWP). Furthermore, progress in climate modelling is intimately linked to progress in NWP. The wind profile measurements provided by ADM-Aeolus are expected to lead to significant improvements in the modelling of atmospheric transport and the analysis of the atmospheric state. This will again lead to better initial conditions for weather forecasting, an improved parameterization of atmospheric processes, and an improved understanding of the global cycling of energy, water, aerosols, and chemicals. These advances will in turn improve 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. ADM-Aeolus further aims to demonstrate its potential for full operational use.

For a mission intended to demonstrate the feasibility of a full-scale space-borne wind observing system, the requirements on data quality and vertical resolution are the most stringent and most important to achieve. The derivation of the horizontal coverage specification is supported by weather forecast impact experiments, which include the inputs of the conventional wind-profile network. The coverage specification is also compatible with the World Meteorological Organisation WMO threshold requirements (e.g. WMO, 2001). Table 1 provides an overview on the ADM-Aeolus requirements.

		PBL	Troposphere	Stratosphere
Vertical Domain	[km]	0-2	2-16	16-20 (30)
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 - 50	
Accuracy (HLOS Component)	[m/s]	1	2	3 (5)
Data Availability	[hour]		3 (0.5)	
Length of Observational Data Set	[yr]		3	

Table 1: **The ADM-Aeolus observational requirements. Goals are shown in brackets.**

Figure 1 illustrates the expected measurement performances versus height.

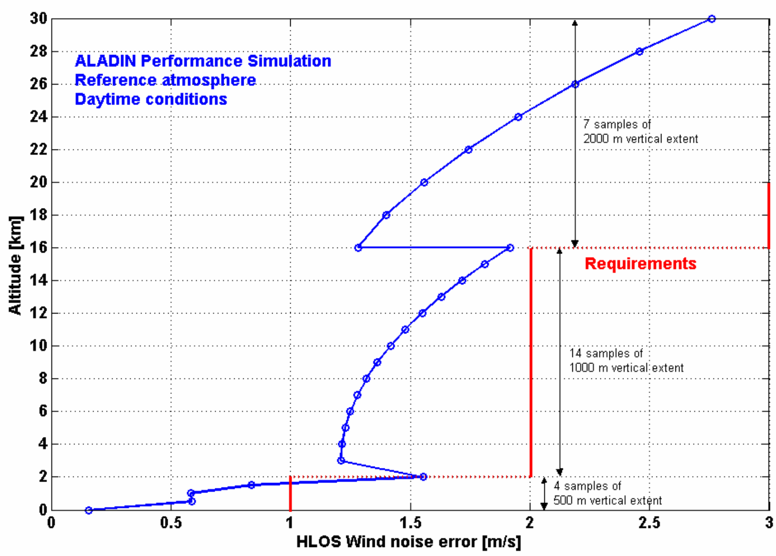

Figure 1: **ADM-Aeolus measurement performance estimates from the surface up to 30 km altitude. The red line indicates the observational requirements as given by Table 1.**

ADM-Aeolus will also be able to deliver height profiles of backscatter and extinction coefficients, and of the lidar ratio (Ansmann et al., 2006). From these parameters it is possible to retrieve cloud and aerosol information such as cloud-top height, the detection of multi-layer clouds and aerosol stratification, cloud and aerosol optical depths (integrated light-extinction profiles), and cloud and aerosol type (lidar ratio).

ADM-Aeolus is also expected to give information on wind variability as caused by e.g. clear-air turbulence. After its products have been thoroughly validated, it can also be used for comparison / validation of other satellite-based wind and aerosol products.

TECHNICAL AND MEASUREMENT CONCEPTS

The ADM laser source is based on a single mode, 120 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 emitted laser pulse is backscattered in the atmosphere by air molecules (Rayleigh scattering) and particles (Mie scattering), and by the Earth's surface. The wind, aerosol and cloud measurements are derived from the measured Doppler shift of the backscattered light along the lidar line-of-sight (LOS) (Fig. 2). The laser will be operated in so-called burst mode where the full observation of 700 shots is taken over typically 7 seconds, followed by a 21 seconds period where the laser is switched off. In this 7-second measurement period the satellite will have travelled approximately 50 km and thus the wind and particle properties fields will have been effectively averaged over this distance in the propagation direction. The vertical height resolution is determined by the length of the time-window chosen for the signal accumulation of the return signal. ADM-Aeolus will provide about 3,000 globally distributed wind and particle properties profiles per day at typically 200 km separation along the satellite track down to the surface for clear air and above thick clouds. Wind information within and below thin clouds or at the top of thick clouds is also attainable. A near real-time delivery of data to the main NWP centres is anticipated.

SCIENTIFIC STUDIES

In the past the scientific studies 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. on high-impact weather, on the preparation for an operational use of the data, on the potential of the ADM-Aeolus additional aerosol and cloud products, and on the adaptation of ADM-Aeolus for full operational use.

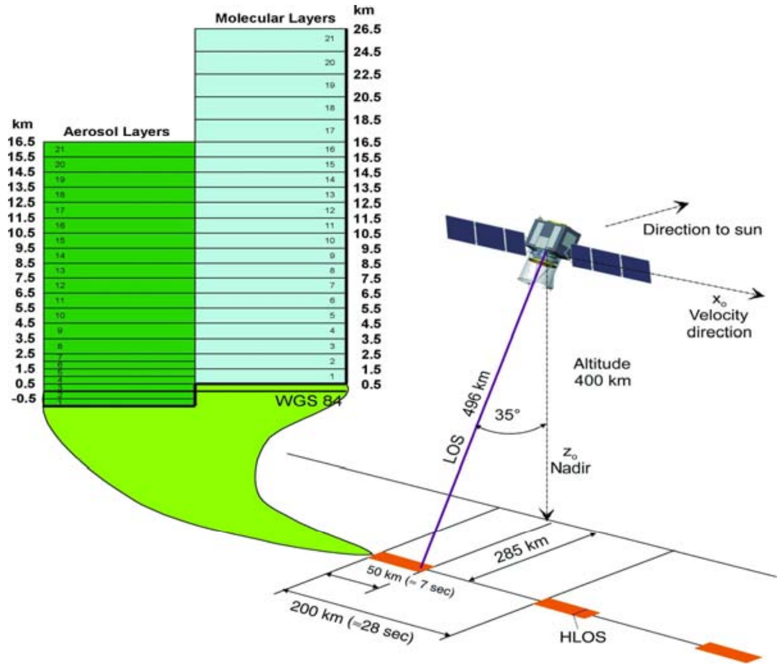

Figure 2: **The ADM-Aeolus measurement and sampling concept: The lidar emits a laser pulse towards the atmosphere, then collects, samples and retrieves the frequency of the backscattered signal. The received signal frequency is Doppler-shifted from the emitted laser light due to the spacecraft motion, the Earth rotation and the wind velocity. The lidar measures the wind projection along the laser line-of-sight (LOS), using a 35° slant angle versus nadir. Also shown is a vertical sampling scenario. The vertical as well as the horizontal sampling can be programmed, providing observation flexibility.**

Ingmann *et al.* (2004) showed the results from two studies focusing on; i) the impact of ADM-Aeolus LOS wind measurements on reducing uncertainties in the analysis fields of equatorial waves (University of Stockholm), and ii) the expected benefits of wind profiles from the ADM-Aeolus mission in a data assimilation system (ECMWF). At Stockholm University, the assimilation of equatorial waves by LOS wind observations was investigated using a shallow-water dynamics framework (Žagar, 2004). Three- and four-dimensional variational data assimilation was used to compare the impact of the LOS winds to the impact of i) wind field information and ii) to measurements of the mass field. The main result from this study was that the LOS wind measurements have the potential to reduce the uncertainty of tropical dynamical fields when used in combination with height (mass field) data. This again leads to an improvement of NWP and climate modelling in the tropics. At the ECMWF, simulated Aeolus measurements were assimilated in Analysis Ensemble experiments. The study concluded that the largest impact of the ADM-Aeolus measurements at the 500 hPa level were found over the oceans, but at the 200 hPa level the impact extended throughout the tropics.

Recently, a study of the added value of space-borne Doppler Wind Lidar (DWL) measurements for the prediction of high-impact weather systems in the Northern Hemisphere extra-tropics was concluded. The study called ‘Prediction Improvement of Extreme Weather’ (PIEW) was performed by the Royal Netherlands Meteorological Institute (KNMI). In this study, a new method was developed for assessing the forecast impact of new observing systems; the so-called Sensitivity Observing System Experiment (SOSE) (Stoffelen et al., 2006). In SOSE, sensitivity structures are used to define a pseudo-truth for the simulation of the new instrument. An OSSE (for February 1993 - used to show the impact of ADM-Aeolus as compared to the present GOS) was successfully exploited to characterise the SOSE method. Unlike OSSEs, SOSEs require only the simulation of the new instrument. In this study, SOSEs have been applied to ADM-Aeolus and candidate follow-on scenarios for a database of cases with bad ECMWF 2-day forecasts. Four of the five different sampling scenarios that were considered in PIEW are shown in Fig. 3. The fifth sampling scenario was a triple-Aeolus, i.e. three Aeolus satellites in one orbit plane, separated by a 120° difference in orbit phase.

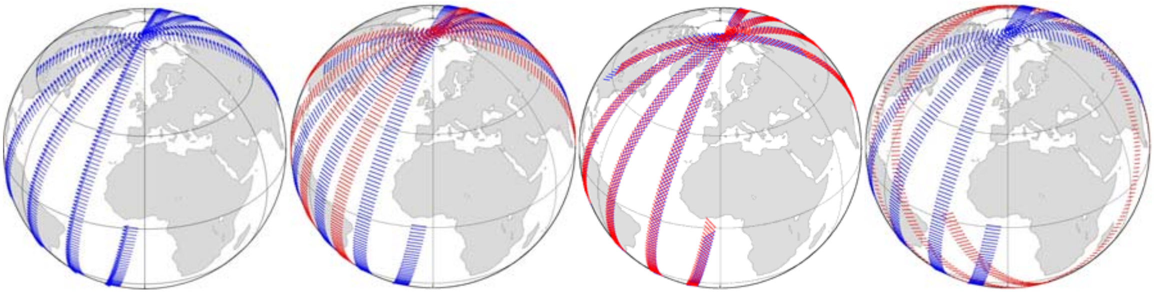

Figure 3: **The ADM-Aeolus scenario sampling single LOS wind components (left), a tandem-Aeolus, i.e. two Aeolus satellites in one orbit plane, separated by an 180° difference in orbit phase (middle - left), Dual-perspective, i.e. two line-of-sights with a 90° difference in azimuth angle in order to measure the complete horizontal wind vector (middle-right), Dual-inclination, i.e. two Aeolus-type satellites in separate orbit planes and with different inclination angles of 97.2° (Aeolus) and 70°, to achieve maximum coverage over the storm-track regions. In addition, this scenario mimics a dual-perspective scenario with Aeolus-type (single LOS) satellites (right). Figures with courtesy of N. Žagar.**

SOSE simulations using simulated measurements from these 5 observation scenarios were run for thirty-eight cases of bad weather predictions. The cases were collected from an ECMWF database of worst 500 hPa geopotential height RMSE forecast scores of the ECMWF operational model from 1/1 1998 to 25/9 2004, and covered all seasons. Both the DWL impact on the 500 hPa wind analysis and a 2-day forecast of the 500 hPa geopotential height was studied. The main conclusion from PIEW was that ADM-Aeolus is capable to resolve part of the analysis error structures in data sparse areas (Table 2). However, measuring wind vector profiles (dual perspective) instead of LOS components over the Northern Hemisphere oceans gives a 50% forecast improvement as compared to the ADM-Aeolus single LOS sampling. An even larger improvement is achieved by the tandem scenario (70% and more).

# of satellites	Scenario	N.Hemis	N.Atlantic	Europe	N.Pacific	N.America	N.Pole
1	ADM-Aeolus	4.9	2.9	2.8	6.6	5.4	9.9
2	Dual view	7.3	3.9	3.8	9.8	8.5	14.1
2	Tandem-Aeolus	8.0	5.0	5.3	11.1	7.4	15.8
2	Dual-inclination	6.6	4.4	4.7	8.5	5.8	10.8
3	Triple-Aeolus	9.8	6.4	8.0	13.1	8.8	18.3

Table 2: **Mean 500 hPa geopotential height 2-day forecast improvements (%) over 38 cases brought by DWL observations from five scenarios relative to the maximum achievable improvement (100%).**

At the time of writing, EUMETSAT is running a study on the potential impact of the PIEW sampling scenarios for capturing tropical dynamics. The simulations are done by Nedjeljka Žagar at the University of Ljubljana in Slovenia in cooperation with the KNMI and the Department of Meteorology at Stockholm University (MISU). As in the previous study on the impact of ADM-Aeolus LOS winds on the tropical dynamics, the assimilation of equatorial waves is investigated using a shallow-water dynamics framework. Tentative conclusions are that wind vector information in the tropics is more important than at mid-latitudes, favouring dual-perspective measurements. As a consequence, it can be concluded that the requirements for a follow-on mission need more in-depth analysis. It is planned to address this in the near future.

The contribution of ADM-Aeolus to a long-term aerosol and cloud optical properties database has been addressed by Albert Ansmann and Ulla Wandinger at the Institute for Tropospheric Research (IfT) in Leipzig, Germany. The objective of the study was to demonstrate the potential of ADM-Aeolus to measure optical properties of aerosol and clouds based on end-to-end simulation studies. The study concluded that ADM-Aeolus is able to provide global sets of trustworthy height-profiles of backscatter and extinction coefficients, and extinction-to-backscatter (lidar) ratios. An example is shown in Fig. 4 for a noisy cirrus case. The estimated relative (statistical + systematic) errors in the retrieved optical properties from ADM-Aeolus are summarized in Table 3. Based on this, the study concluded that ADM-Aeolus is able to contribute to a long-term dataset of aerosol and cloud optical properties from CALIPSO to EarthCARE (scheduled launch: 2012).

	Layer (ext. value)	**$\delta\beta_a/\beta_a$ Backscatter**	**$\Delta\sigma_a/\sigma_a$ Extinction**	**$\delta S_a/S_a$ Lidar ratio**
Haze Layer	PBL (σ_a = 200 Mm^{-1})	5%-10%	15% - 30%	20% - 35%
Lofted Smoke	FTA (σ_a = 50 Mm^{-1})	5%-15%	25% - 50%	30% - 50%
Cirrus	CI (σ_a = 200 Mm^{-1})	15%-20%	25% - 30%	30% - 50%
Strat. Aerosol	SA (σ_a = 10 Mm^{-1})	10%-15%	>100%	>100%
Pol. Strat. Clds.	PSC (σ_a = 20 Mm^{-1})	10% - 15%	50%-100%	50%-100%

Table 3: **Estimated relative (statistical + systematic) error in the retrieved optical properties from ADM-Aeolus. Additional errors are uncertainties in multiple scattering effect and cirrus extinction: ~20%, and depolarization effect in cirrus, Polar Stratospheric Clouds (PSCs) and desert dust backscatter: ~20%.**

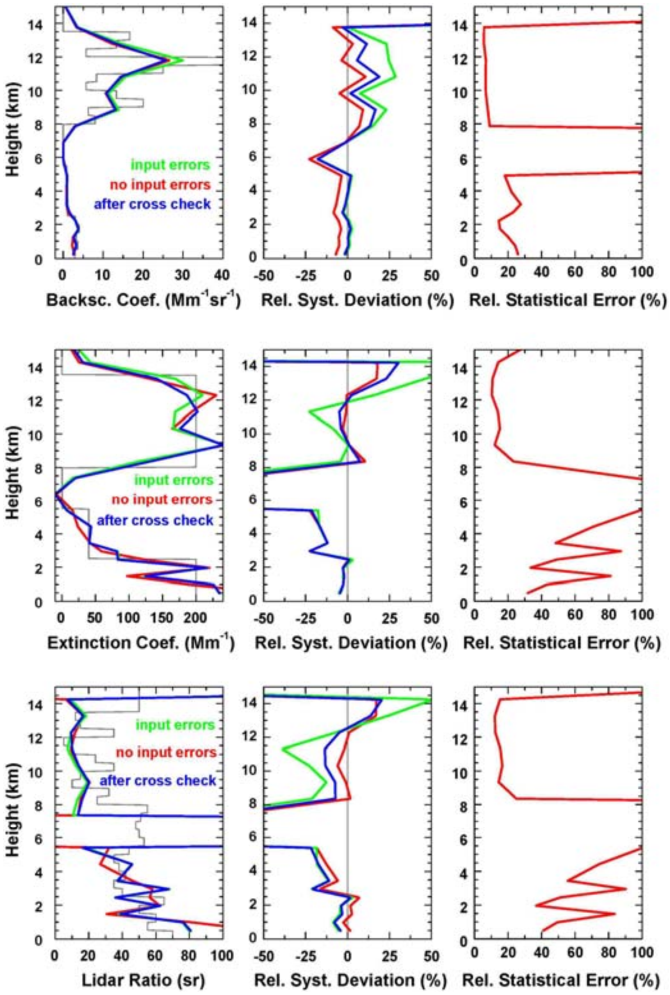

Figure 4: **Left column: Simulated observations (350 shot average) of particle optical properties (backscatter coefficient – top panel, extinction coefficient - middle panel, and Lidar ration - lower panel) with the ADM-Aeolus ALADIN laser (High Spectral Resolution method). Grey curves: True profiles (50 m vertical resolution). Red curves: No atmospheric and lidar system parameter errors. Green curves: simulating realistic errors in all input parameters. Blue curves: After applying a quality check for the cross-talk correction. Middle column: Systematic deviation of the retrieved solutions from the ALADIN signal simulation input profiles. Right column: The statistical error caused by signal noise.**

ADM-Aeolus was presented to Stratospheric Processes And their Role in Climate (SPARC) during the Banff workshop in September 2005, making the stratospheric research community aware of the mission. A strong interest was expressed by the SPARC community, and a study demonstrating the impact of ADM-Aeolus wind measurements on stratospheric research including dynamics and chemistry is being initiated at the time of writing.

CAMPAIGNS

Ground-based and airborne measurements and validation of the Aladin Airborne Demonstrator (A2D) will demonstrate the capability of the ADM-Aeolus space-borne Doppler wind lidar Aladin. The campaign planning is listed in table 4.

Campaign	Location	Period	Duration
Aeolus Ground Campaign AGC	DWD-MOL Lindenberg	Autumn 2006	4 weeks (+1 week)
Aeolus Campaign 1	DLR Oberpfaffenhofen, Lindenberg	Spring 2007	15 days / 25 hours
Aeolus Campaign 2	TBD about 1yr in advance	Autumn 2007	17 days / 50 hours

Table 4: **The A2D validation campaign planning.**

Installation and testing of the A2D on ground was performed with first atmospheric signal in October 2005. The two functional test-flights were performed with signal from clear atmosphere, clouds and ground. The measurements demonstrated that the aircraft integration and testing was successful. These were probably the first flights of an airborne, direct-detection Doppler wind lidar worldwide.

CONCLUSIONS

Accurate wind profile observations are needed to improve NWP and climate analysis. A feasible concept for a Doppler wind lidar demonstrator (ADM-Aeolus) has been developed and will be implemented as the second Earth Explorer Core Mission. The ADM-Aeolus industrial Phase C/D started in October 2003. Various scientific and campaign activities are being and will be performed in parallel to the technical activities. These have demonstrated the improvement of NWP forecasting through the inclusion of ADM-Aeolus measurements in the global observation system. Furthermore, the contribution of ADM-Aeolus measurements of aerosol and clouds optical properties to a long-term database from CALIPSO to EarthCARE has been demonstrated. The ADM-Aeolus launch is scheduled for late 2008. The further adaptation of ADM-Aeolus for full operational use is being studied.

REFERENCES

Ansmann, A., Ingmann, P., Le Rille, O., Lajas, D., and Wandinger, U., (2006) Particle Backscatter and Extinction Profiling with the Spaceborne HSR Doppler Wind Lidar ALADIN, Proceedings from the 23rd International Laser Radar Conference, Nara, Japan, submitted.

European Space Agency (ESA), (1989) ALADIN - Atmospheric Laser Doppler Instrument. Working Group Report, ESA SP-1112, 45p.

European Space Agency (ESA), (1999) Atmospheric Dynamics Mission. Report for Mission Selection, ESA SP-1233(4), 157p.

Ingmann, P., Endemann, M., and the members of the ADMAG (2004) Activities in Support of the Doppler Wind Lidar Profiling Mission ADM-Aeolus. Proceedings of the 7th International Winds Workshop, Helsinki, Finland, pp 405-413.

Stoffelen, A., Pailleux, J., Källén, E., Vaughan, J. M., Isaksen, L., Flamant, P., Wergen, W., Andersson, E., Schyberg, H., Culoma, A., Meynart, R., Endemann, M. and Ingmann, P., (2005) The

Atmospheric Dynamics Mission for Global Wind Measurement. Bull. Amer. Meteorol. Soc., **86,** pp 73-87.

Stoffelen, A., Marseille, G.J., Barkmeijer, J., (2006) SOSE: Sensitivity Observing System Experiment; Doppler Wind Lidar Impact in Extreme Weather. Proceedings of the 8th International Winds Workshop, Beijing, China, this issue.

World Meteorological Organisation (WMO), (2001) Statement of Guidance Regarding How Well Satellite Capabilities Meet WMO User Requirements in Several Applications Areas. Sat-26, WMO/TD No.1052, 52p.

Žagar, N., (2004) Assimilation of Equatorial Waves by Line of Sight Wind Observations. J. Atmos. Sci., **61**, pp 1877-1893.

---

[1] E. Andersson / ECMWF, A. Dabas / Météo France, P. Flamant / LMD, E. Källén / MISU, P. Menzel / NOAA, D. Offiler / UKMO, O. Reitebuch / DLR, L.-P. Riishøjgaard / NASA-GSFC/GMAO, H. Schyberg / met.no, A. Stoffelen / KNMI, M. Vaughan / MMA, W. Wergen / DWD