P6.4 PREPARATIONS FOR USE OF DOPPLER WIND LIDAR DATA FROM THE ATMOSPHERIC DYNAMICS MISSION (ADM-AEOLUS) IN DATA ASSIMILATION & NUMERICAL WEATHER PREDICTION

D.G.H. Tan* and E. Andersson
ECMWF, Shinfield Park, Reading, U.K.

1. INTRODUCTION

The Atmospheric Dynamics Mission (ADM-Aeolus) is the third mission in ESA's Living Planet/Earth Explorer Programme and its second Core Mission (ESA 1999, Stoffelen et al. 2005, more generally http://www.esa.int/export/esaLP/index.html). With a launch planned around October 2007 and an envisaged lifetime of three years, its objective is to demonstrate the capability to measure wind profiles from space using a Doppler Wind Lidar (DWL). Aeolus is designed to provide high-quality wind profiles from the surface up to 27 km, at a rate of around 100 profiles per hour. In the atmosphere's baroclinic regions, the need for good vertical resolution data and the prevalence of cloud pose severe challenges for the global observing system. Active remote sensing by lidars can potentially meet both these challenges. This paper describes the preparations that are being made in order to use Aeolus data in global data assimilation and numerical weather prediction (NWP) systems. These preparations include detailed simulations of Aeolus data (Marseille and Stoffelen 2003, Tan and Andersson 2005a) and assimilation ensemble experiments to assess the impact of such data in the ECMWF Integrated Forecast System (Tan and Andersson 2005b).

2. ADM-AEOLUS OBSERVATION REQUIREMENTS

The Aeolus DWL is known as ALADIN (Atmospheric Laser Doppler Instrument). It is a non-scanning instrument with an orientation fixed relative to the satellite (Figure 1). For details on the operating principles and design characteristics of the Aeolus DWL, the reader is referred to Marseille and Stoffelen (2003), Stoffelen et al. (2005) and the references therein. The instrument has both a Rayleigh channel, to detect the Doppler shift induced by the motion of molecules, and also a Mie channel, for the Doppler shift induced by particles (primarily cloud and aerosol). Both channels use direct-detection receivers, sharing a transmitter laser operating in the ultraviolet (355 nm).

Under nominal operations the DWL will provide layer-averaged wind measurements with a 1000 m vertical resolution through most of the atmosphere (i.e. from 2 to 16 km), 500 m below 2 km and 2000 m between 16 and 20 km. There is provision to make measurements up to at least 27 km, and flexibility to adjust the vertical resolution during flight (down to a minimum of 250 m). The primary wind information from a non-scanning DWL is a profile of the so-called HLOS (horizontal line-of-sight) wind component. For the Aeolus/ALADIN viewing geometry, the HLOS wind component is the projection of the wind vector in the direction perpendicular to the satellite ground track. The polar orbit planned for Aeolus has an inclination of approximately 97 degrees, and so the Aeolus HLOS wind information is nearly zonal in the Tropics, nearly meridional at very high latitudes, with a gradual transition in between (Figure 2). While the Rayleigh and Mie channel Doppler shifts are intended to provide wind information, the Mie channel signal strengths may themselves provide additional information on cloud and aerosol properties (backscatter, extinction, loading).

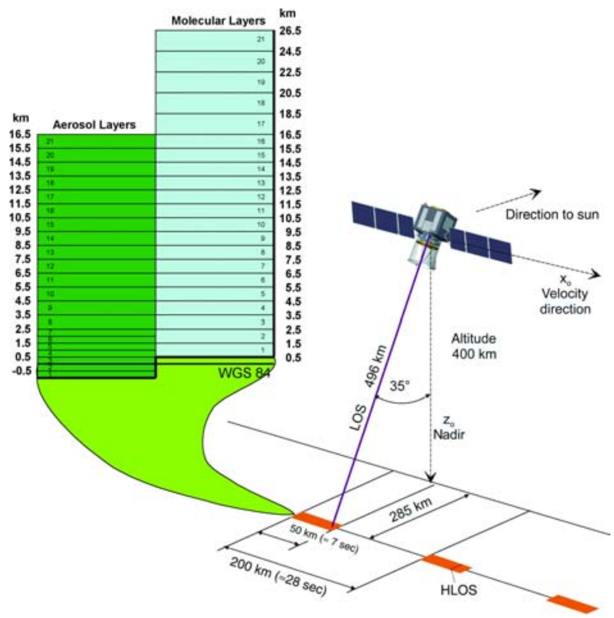

Figure 1 ADM-Aeolus viewing geometry and vertical resolution (Courtesy ESA)

The horizontal and temporal coverage of ADM-Aeolus data will be determined by the satellite's orbital parameters, the non-scanning viewing geometry, and the duty cycle of the DWL. Successive observation locations will be separated in time by 28 seconds and in space by 200 km along the observation ground track, which itself runs parallel to the satellite ground track. Adjacent tracks will be separated in time by the orbit period (~90 minutes) and by ~2500 km at the Equator (Figure 2). A non-scanning DWL is a highly directional

* *Corresponding author address*: David G.H. Tan, ECMWF, Shinfield Park, Reading, RG2 9AX, U.K.; e-mail: David.Tan@ecmwf.int.

instrument and this is further reflected in the disparate magnitudes of the horizontal integration lengths, which for Aeolus are 50 km along-track and 10m cross-track. The integration lengths provide a degree of averaging which improves accuracy and representativeness.

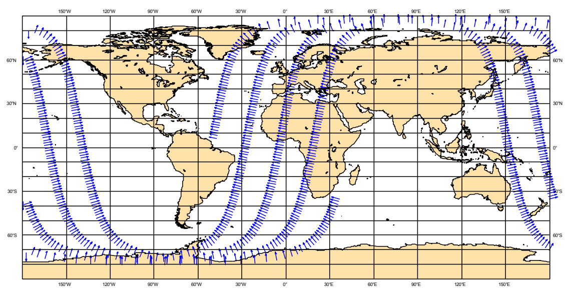

Figure 2 ADM-Aeolus coverage and HLOS directions (6 hour period)

The Aeolus observation requirements have been developed to meet scientific goals of user communities in climate research, atmospheric modeling and numerical weather prediction (ESA 1999, Stoffelen et al. 2005). In particular the observation separations have been chosen to provide a high degree of independence between successive observations, assuming that systematic errors can also be kept small. This independence is achieved by ensuring that the observation separations are greater than the decorrelation length scales of the background error structures adopted in data assimilation schemes (~200 km, Hollingsworth and Lönnberg 1986, Xu and Wei 2001). More densely spaced observations are effectively filtered by data assimilation procedures (Rabier et al. 1998) and hence are less efficient (for the same number of laser shots) at providing information for atmospheric analysis.

The characteristics of the transmitter and receivers have been chosen to obtain random errors below 2 m/s between 2 and 20 km altitude, and below 1 m/s between 0 and 2 km. The error realized will depend primarily on the intensity of the backscattered laser light, which in turn depends on the effects of cloud and aerosol on the propagation of the laser beam. For example, the Rayleigh channel is designed to provide good data in cloud-free areas and above cloud tops, and in some partially cloudy areas, e.g. where transmission through thin cirrus is sufficiently strong, and in gaps between broken cloud. These are to be complemented by Mie channel data, in regions where particulate backscatter is sufficiently strong.

3. LIPAS SIMULATIONS OF AEOLUS DATA

To date, preparations for Aeolus have made use of simulated data obtained from LIPAS (LIdar Performance Analysis Simulator, Marseille and Stoffelen 2003). Simulations have been conducted for a number of periods, with different input data to the simulator. For example, Tan and Andersson (2005a) examine the period 9th to 18th September 1994, during which an observed cloud cover product derived from LITE data is available (Miller et al. 1999). Their study found that when the observed cloud cover is replaced by model fields, the sensitivity of the LIPAS simulations to the assumed cloud cover is small. The simulations described here are for 10th January to 28th February 2003, corresponding to the period chosen for the assimilation ensemble experiments described later. Wind profiles supplied as input to the simulator were taken from Met Office analyses. Other meteorological inputs were taken from the ECMWF operational archive. Aerosol backscatter was taken from the median profile of a climatology derived from observational data obtained during airborne lidar campaigns (Vaughan et al. 1995). These data include low-, mid- and high-latitude observations taken over the Atlantic ocean during 1988—1990, and were adapted to the Aeolus wavelength within LIPAS.

Figure 3 shows the geographical distribution of expected Aeolus yield for the altitude range 9--10 km. Simulated Aeolus data for 1 week have been grouped in 5 by 5 degree bins. Within each bin, the percentage of simulated data that meet the mission accuracy requirements is calculated (coloured markers). To relate the performance of the Rayleigh and Mie channels to the cloud cover encountered, the figure also shows root-mean-square of high cloud cover (shaded).

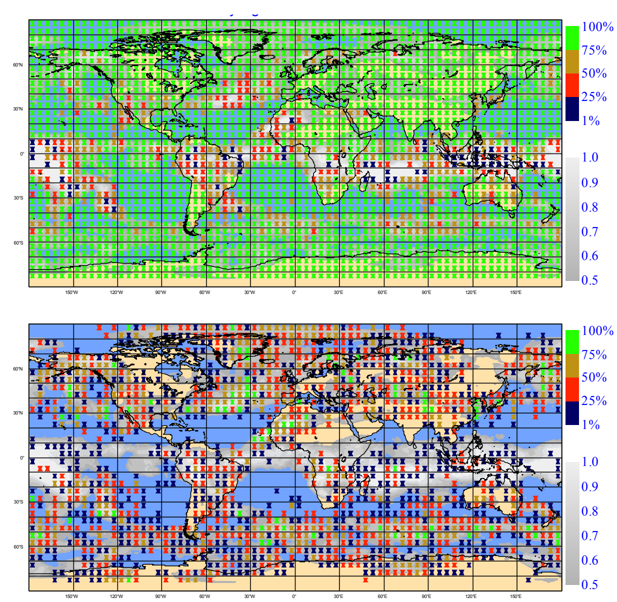

Figure 3 Percentage of data at 9-10 km with random error < 2 m/s, Rayleigh and Mie channels (upper and lower panels). Data simulated for 1 week and grouped in 5 by 5 degree bins. Shading: ECMWF high cloud cover (root-mean-square)

There is a close correspondence between good Rayleigh channel performance and low amounts of cloud cover. LIPAS models the expected ability of the

Rayleigh channel to probe in cloud gaps, resulting in reasonable performance in areas with moderate amounts of cloud cover. Conversely, high amounts of cloud cover results in good data from the Mie channel, at least from the cloud tops.

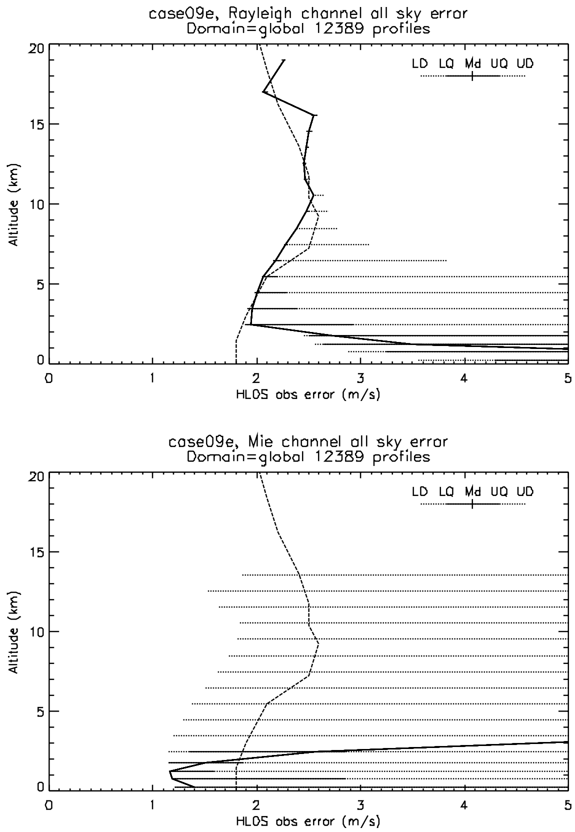

Figure 4 Error profiles including representativeness error for a 50 km grid box.

After accounting for errors of representativeness, the error distribution of simulated Aeolus observations as a function of altitude is shown in Figure 4. The thick solid curve connects the median error at each altitude and thus depicts a "typical" error profile. Above 11 km, cloud effects are small and compact error distributions for the Rayleigh channel are evident. The reduction in errors above 16 km is associated with the change in vertical resolution from 1 km to 2 km. The Rayleigh channel distributions exhibit increasing skewness at lower altitudes, associated with poor data below thick cloud. The poor data are easily identifiable by their low signal-to-noise ratio and can be removed from further processing by the users of future Aeolus data, via suitable (user-dependent) quality control procedures. The identification of poor data thus affects yield rather than accuracy of the final product. It is interesting to note that the best 10% of Mie channel data have errors below 2 m/s up to 14 km. The observation errors shown in Figure 4 are inversely proportional to the weight the data would receive in data assimilation schemes, subject to adjustment for specific background error covariance structures. The ECMWF radiosonde observation errors are shown for reference as the thick dashed curve. Aeolus data are thus expected to receive weight comparable to that given to each wind component of radiosonde and wind profiler observations.

4. ASSIMILATION ENSEMBLES & DATA IMPACTS

The expected impact of ADM-Aeolus data has been investigated through a series of assimilation ensemble experiments. The original motivation for the assimilation ensemble method stems from the need to estimate background errors for use in the ECMWF assimilation system (Fisher 2003a, Žagar et al. 2005). For this purpose the method consists of generating an ensemble of analyses and associated short-range forecasts. Each ensemble member is an independent run of the ECMWF 4d-Var analysis/forecast system. The observations supplied to the analysis system differ between ensemble members, through the addition of random perturbations consistent with the observation errors assumed in the analysis system. That is, the observation perturbations are spatially uncorrelated and each is drawn from a Gaussian distribution with standard deviation specified by the observation error of the observation under consideration. The underlying premise of the method is that differences in contemporaneous short-range forecasts, arising from different ensemble members, are a useful surrogate for background errors. The method has been used to construct the background error statistics used in the ECMWF variational analysis since October 1999 (Fisher 2003a), and to formulate a new humidity analysis (Hólm et al. 2002). The ensemble data have also been used for Aeolus-related studies of wind errors in the ECMWF system (Tan and Andersson 2005a) and of wind-mass balance relationships in the tropics (Žagar et al. 2005).

Here, the assimilation ensemble method is extended to assess the impact of different observations types (simulated Aeolus data and, for calibration purposes, radiosonde/wind profiler data). This has required the generation of new ensembles that differ in the observations made available to the ensemble method. Four ensembles have been generated, and each ensemble consists of 4 independent members; each member is run for the period 10^{th} January to 28^{th} February 2003. The four ensembles differ in the observations that are perturbed and assimilated as follows:

- **Control**: All observational data used in the 2004 ECMWF operational system,
- **DWL**: Control with simulated Aeolus data added,
- **NoSondes**: Control with radiosondes and wind-profilers removed,
- **DWL-NoSondes**: NoSondes with simulated Aeolus data added.

Statistics, such as the spread in a particular ensemble, are compiled for the period 16 Jan to 28 Feb 2003 (to disregard common initial conditions). A beneficial impact of observational data should correspond to a reduction in ensemble spread. Comparison of the Control and NoSondes ensembles permits essential calibration of the technique.

The approach of removing real observation types (or adding simulated ones) in the assimilation ensemble method resembles the approach taken in traditional Observing System (Simulation) Experiments (OSEs/OSSEs). There are two perceived advantages of the assimilation ensemble method over OSSEs for data impact studies. The first is that, for existing observation types, the ensemble method perturbs real observations and thus eliminates the need to simulate such observations from a common nature run; a reference run is required only for simulating new observation types such as Aeolus HLOS wind data. The second is that the data impact measures in the ensemble method are based on relative differences such as ensemble spread, and are thus thought to be less sensitive than OSSE impact measures to the uncertainties surrounding the treatment of observation/simulation bias and verification against a nature run. This paper acknowledges however that the assimilation ensemble method for data impact assessment is entirely new and that many aspects of its performance remain un-explored.

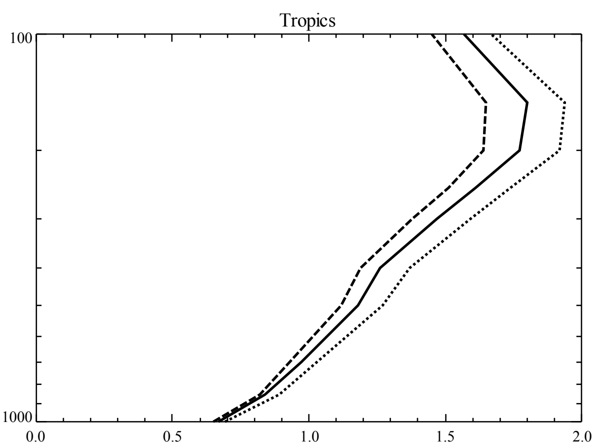

Figure 5 Spread in zonal wind (m/s) from the 12-hour forecasts from 3 assimilation ensembles. Solid: 2004 observing system, dotted: radiosondes and wind profilers removed, dashed: simulated Aeolus data added. A scaling factor of order 2 is required to obtain values commensurate with background errors in NWP models

Figure 5 shows the ensemble spread between 12-hour forecasts, averaged over the Tropics, for the Control, DWL and NoSondes ensembles. A calibration factor of order 2 is required to obtain values commensurate with actual wind errors in NWP models. It is evident nonetheless that the impact of simulated Aeolus data compares favourably with radiosonde/wind-profiler data. The largest spreads are found near, or just below, the tropopause. Apart from the small differences between the DWL and Control profiles between 1000 and 850 hPa, all other differences are found to be significant according to Student's T-test ($p<0.001$).

The examples just presented suggest that the impact of simulated Aeolus data are comparable to the impact of radiosondes/wind-profilers in terms of assimilation ensemble spread. This comparability has been found to extend to two global diagnostics of information content for the two data types. The two measures examined are the entropy reduction, as measured by information bits contributed to the analysis, and the degrees of freedom for signal (DfS) in the data (Rodgers 2000). Fisher (2003b) describes the computational scheme to estimate these quantities within the ECMWF system. The calculations are based on current background error statistics and current used observations (January 2003) with the addition of AIRS data (which in operations were being passively monitored at the time). The results (Table 1) are in keeping with the quantity, accuracy and coverage of the simulated Aeolus data. Radiosondes and wind profilers provide more information in absolute terms, but require proportionately more observations to achieve this. Aeolus observations are more "efficient" at providing information per datum because they are able to contribute information in regions that are currently poorly observed, i.e. over ocean regions in both hemispheres and throughout the tropics.

	Sondes & wind profilers	ADM-Aeolus Doppler wind lidar
Data	u,v to 55 hPa	HLOS (simulated)
Information bits	4203	2787
DFS	3153	2454
Number of data	74682	28979
Information bits per datum	0.056	0.096
Data per DFS	23.7	11.8

Table 1: Information content by data type (12-hour observation window)

5. ON-GOING PREPARATIONS

ADM-Aeolus is now in Phase C. Activities to realize the space and ground segments currently include production and testing of the DWL components, as well as development of the ground-processing algorithms. Ground-based and airborne campaigns are planned for the purposes of testing algorithms. Provision has been made for detailed planning of the calibration and validation activities that will be required during the in-orbit commissioning phase. A number of scientific studies are in progress, ranging from investigations into physical processes (scattering and line shapes) affecting the wind retrieval algorithms, to climate- and dynamics-related applications of the HLOS wind profile data (building on, e.g., Žagar et al. 2004).

At the request of ESA, development studies for the wind-retrieval algorithms are being conducted under the lead of Météo-France, assisted by other institutions including ECMWF. It is intended to make a portable version of the software widely available to the scientific/meteorological community. A major design consideration has been to cater for operational centres with (near-) real-time requirements. The automated detection and classification of clouds within the DWL field-of-view, and consequent decisions about selective averaging of the lidar signals, are expected to feature prominently in the retrieval algorithms.

Work funded by ESA Study Contract No 15342/01/NL/MM. DT is on secondment from the UK Met Office.

REFERENCES

European Space Agency, 1999: The four candidate Earth Explorer Core Missions - Atmospheric Dynamics Mission. **ESA SP-1233(4),** pp 157.

Fisher, M., 2003a: Background error covariance modeling. Proc. ECMWF Seminar on "Recent Developments in Data Assimilation for Atmosphere and Ocean", 8-12 Sept 2003, Reading, U.K., 45—63. http://www.ecmwf.int/publications/library

Fisher, M., 2003b: Estimation of entropy reduction and degrees of freedom for signal for large variational analysis systems. *ECMWF Tech Memo*, **397,** pp 18. http://www.ecmwf.int/publications/library

Hollingsworth, A. and P. Lönnberg, 1986: The statistical structure of short-range forecast errors as determined from radiosonde data. Part I: The wind field. *Tellus,* **38A,** 111—136.

Hólm, E., E. Andersson, A. Beljaars, P. Lopez, J-F. Mahfouf, A. J. Simmons and J.-N. Thépaut, 2002: Assimilation and modeling of the hydrological cycle: ECMWF's status and plans. *ECMWF Tech. Memo*., **383,** pp 55. http://www.ecmwf.int/publications/library

Marseille, G.-J. and A. Stoffelen, 2003: Simulation of wind profiles from a space-borne Doppler wind lidar. *Q. J. R. Meteorol. Soc.,* **129,** 3079—3098.

Miller, S. D., G. L. Stephens and A. C. M. Beljaars, 1999: A validation survey of the ECMWF prognostic cloud scheme using LITE. *Geophys. Res. Lett.,* **26,** 1417—1420.

Rabier, F., A. McNally, E. Andersson, P. Courtier, P. Undén, J. Eyre, A. Hollingsworth and F. Bouttier, 1998: The ECMWF implementation of three-dimensional variational assimilation (3D-Var). II: Structure functions. *Q. J. R. Meteorol. Soc*. **124,** 1809—1829.

Rodgers, C. D., 2000: Inverse Methods for Atmospheres: Theory and Practice. *Series on Atmospheric, Oceanic and Planetary Physics, World Scientific Publ., Singapore,* pp 238.

Stoffelen, A., J. Pailleux, E. Källén, J. M. Vaughan, L. Isaksen, P. Flamant, W. Wergen, E. Andersson, H. Schyberg, A. Culoma, R. Meynart, M. Endemann and P. Ingmann, 2005: The European Atmospheric Dynamics Mission ADM-Aeolus for global wind field measurement. *Bull. Am. Meteorol. Soc.,* in press.

Tan, D. G. H. and E. Andersson, 2005a: Simulation of the yield and accuracy of wind profile measurements from the Atmospheric Dynamics Mission (ADM-Aeolus). *Q. J. R. Meteorol. Soc.,* submitted.

Tan, D. G. H. and E. Andersson, 2005b: Impact of simulated ADM-Aeolus wind profiles in the ECMWF Integrated Forecast System: an assimilation ensemble approach. *In preparation.*

Vaughan, J. M., D. W. Brown, C. Nash, C. B. Alejandro and G. G. Koenig, 1995: Atlantic atmospheric aerosol studies 2. Compendium of airborne backscatter measurements at 10.6µm. *J. Geophy. Res.,* **100(D1),** 1043—1065.

Xu, Q. and L. Wei, 2001: Estimation of three-dimensional error covariances. Part II: Analysis of wind innovation vectors. *Mon. Wea. Rev.*, **129,** 2939—2954.

Žagar, N., N. Gustafsson and E. Källén, 2004: Variational data assimilation in the tropics: the impact of a background error constraint. *Q. J. R. Meteorol. Soc.,* **130,** 103—125.

Žagar, N., E. Andersson and M. Fisher, 2005: Balanced tropical data assimilation based on a study of equatorial waves in ECMWF short-range forecast errors. *Q. J. R. Meteorol. Soc.,* in press.