AEOLUS PREPARATIONS AND INDICATIONS OF NWP IMPACT

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Abstract
The launch of ESA’s Aeolus Doppler wind lidar satellite mission will be relatively soon: in late 2015, so it is important to be prepared for its exploitation in NWP. This paper explains some features of the measurement principle, what products should be assimilated for NWP, indications of the quality of the wind observations from detailed simulation studies and finally some investigations with OSEs indicating the impact of Aeolus-like wind observations in the ECMWF system.

1. INTRODUCTION

Aeolus is the second of ESA’s Earth Explorer core missions (see ESA’s Aeolus science report). The objective is to provide profiles of high-quality wind observations from the surface to 30 km, using a Doppler wind lidar (DWL) instrument in a near-polar sun-synchronous orbit. The wind information is the horizontal line-of-sight component, perpendicular to the satellite track. The mission is intended to have a lifetime of three years.

ECMWF is leading the project to develop Aeolus Level 2B/C processing software, that is, the wind retrieval and data assimilation of Aeolus winds, and to implement the processing within ECMWF as part of the mission ground segment. The L2B wind retrieval algorithms have been developed over many years in collaboration with partners at KNMI, Météo-France, DLR and LMD/IPSL. Aeolus also provides information on cloud and aerosol optical properties (the L2A product).

Wind profile observations are still lacking in the Global Observing System (GOS), therefore the NWP community is keen to obtain more. There is an expectation for a useful positive impact from Aeolus observations, if the mission specifications can be met. ECMWF has also contributed to a number of data impact studies to assess the potential of the Aeolus data, which suggest it may have a useful positive impact on analysis and forecast quality, particularly in the tropics.

The launch for Aeolus is expected (at the time of writing) to be in late 2015 which is delayed by a year compared to the date reported at IWW11, however we have never been so close to a launch date.

2. MEASUREMENT PRINCIPLE

Aeolus is a direct detection DWL (e.g. see Reitebuch 2012a, b), which means that it is measuring photon counts received through optical filters (filtering in frequency space). The counts received by the spectrometers (e.g. Fabry-Pérot and Fizeau) provide information about the frequency of the backscattered light from the atmosphere. To know what the measured photon counts mean in terms of frequency they have to be calibrated as a function of laser frequency during a separate calibration procedure. This is a downside to the direct detection technique compared to the alternative coherent detection technique which does not require such calibration procedures.

Aeolus will measure the frequency change (relative to that emitted by the telescope) of backscattered laser light scattered from atmospheric molecules and particles. The frequency change is proportional to the average velocity component of the scattering medium in the telescope’s line of sight through the Doppler effect; this average motion of the scattering volume is considered to be the wind. The laser wavelength was chosen to be approximately 355 nm (UV) to allow sufficient backscatter from the molecules (Rayleigh scattering) to obtain wind observations from clear atmosphere (i.e. no cloud/aerosol). This wavelength is also sensitive to particulate backscatter (Mie);
hence winds from regions of aerosol and from the top of dense clouds, and throughout optically thin clouds can be obtained.

The default sampling of the horizontal line-of-sight (HLOS) wind profiles is one profile every ~90 km along the ground-track of the satellite pointing off-nadir by 35 degrees. Horizontal averaging of laser pulses is needed to reach an appropriate signal-to-noise ratio to obtain HLOS winds of order 2 m/s accuracy. Each wind observation will have a resolution of between 0.25-2 km vertically, and 10 m across-track and typically between 10-100 km along track. The horizontal averaging is controllable in the L2B processor. Better quality winds can be achieved with less horizontal averaging for the Mie winds compared to the Rayleigh winds (e.g. 20 km for Mie, and 100 km for Rayleigh for similar quality). This is because the Mie backscattered spectrum is narrow compared to the Rayleigh (which is Doppler broadened due to thermal motions of molecules), and the mean of a narrow distribution can be determined with greater accuracy.

Up to 24 HLOS winds are available per profile, from the surface (if cloud/aerosol-free) up to 30 km altitude. The Aeolus Rayleigh winds will be sampling the lower stratospheric winds to a much greater extent than any other available observation type. It is estimated that Aeolus will provide around 72 thousand HLOS winds per 12 hours that are suitable for assimilation. They will be distributed with a typical polar orbiting coverage. ECMWF assimilates approximately 630 thousand wind components per 12 hours; therefore Aeolus could increase this number by ~11%.

3. WINDS FOR NWP — L2B PRODUCT

The winds for data assimilation are the Level-2B processor HLOS winds. They are geolocated by their geometric height, latitude, longitude, azimuth angle (direction of laser pointing in the horizontal plane) and time. A nice feature of the software is that error estimates for each wind are provided as calculated from the estimated noise levels (mainly due to shot noise with Poisson statistics). Each wind comes with quality flags.

The L2B processor flexibly classify the measurement-level data (accumulation of 20 laser pulses, covering 2.88 km horizontally) into wind types – “cloudy” or “clear” based on estimates of the scattering ratio (amount of particulate backscatter relative to total backscatter), such that “Rayleigh-clear” and “Mie-cloudy” winds can be retrieved with minimal contamination of the Rayleigh by the particulate (Mie) signal. The processor allows for flexible horizontal averaging of the measurementscale spectrometer counts (i.e. choosing the Grouping length-scale), giving some control of noise and representativity of observations (i.e. how much averaging over the turbulent wind field is required for your application and how much reduction of instrument noise is needed).

In the L2B processor the Rayleigh winds are corrected for the influence of atmospheric temperature, pressure and Mie cross-talk (for T and p this requires some a priori estimates which will be provided by NWP short-range forecasts). These corrections are necessary to get unbiased Rayleigh HLOS winds (however the sensitivity of HLOS errors to NWP background error is small e.g. 0.1 ms⁻¹/K). Many of the L2B processing options are controllable from a settings file.

Potential users should be aware that Aeolus is a research mission; therefore we encourage users to experiment with L2B processor so that the NWP community can achieve a suitable product for assimilation/research sooner. Therefore the L2B processor software package is made available to download (e.g. for use by NWP centres): http://www.ecmwf.int/en/research/projects/aeolus

The download website provides the code, documentation and test data. See the Algorithm Theoretical Baseline Document (ATBD, in the documentation) for a detailed description of the L2B product. The L2Bp is designed to be highly portable code (mostly in Fortran90). A new version of the processor (2.10) that includes a L2B EE-to-BUFR converter and much improved runtime speed and various bug fixes will be available soon.

4. SIMULATING AEOLUS WINDS

Before the launch of Aeolus a very useful preparation is to simulate Aeolus and to produce the L2B products to confirm that the operational processing chain is working correctly. Figure 1 shows the steps involved: simulation of Aeolus raw data; running of the operational chain of processors (KNMI software, by Jos de Kloe, controls this chain); verification of the L1B and L2B wind products against the inputs to the simulator (the inputs are defined as the “truth”).
The simulation process can only be reasonably realistic if the meteorological inputs also are (and the simulator forward model is accurate). In this example the optical properties, i.e. atmospheric backscatter/extinction coefficient profiles, are believed to be of reasonable accuracy since they were derived from CALIPSO lidar data (a half-orbit valid on 1st January 2007). Figure 2 shows the derived CALIPSO logarithm to base 10 of the scattering ratio valid at 355 nm wavelength (as part of the KNMI atmospheric database, see Marseille et al. 2011); the CALIPSO profiles are spaced every 3.5 km.

Figure 1. Steps of the simulation of Aeolus and running of the operational processing.

Figure 2. Example simulator input $\log_{10}$ (scattering ratio) along the ground-track of the orbit as a function of altitude. The orbit is also shown on a map (courtesy of NASA, CALIPSO) and the type of particulate scattering feature is indicated. This scenario was derived from CALIPSO data to be valid at 355 nm in the KNMI atmospheric database.
The other necessary meteorological inputs to the simulator are: HLOS wind (actually just \( u \)-component wind in this case), temperature and pressure. These are typically extracted from the ECMWF model and co-located with the CALIPSO half-orbit. The top plot of Figure 3 shows the simulator input HLOS wind (i.e. ECMWF \( u \)-component wind field). The simulation software itself (called E2S) is provided by ESA; it is believed to be accurate after many years of validation and improvement.

The bottom plot of Figure 3 shows the resulting L2B Rayleigh-clear HLOS winds (~90 km horizontal averaging per observation). It is striking how complete the Rayleigh HLOS wind coverage is along the orbital track. There are good winds (as compared to truth) for most of the “curtain” from near the surface to 28 km. The occasional gaps are where optically thick cloud/aerosol exists (nearly all due to cloud in this scene). Cross-sections of the jet streams at around 10-15 km are being captured very well in the L2B product.

*Figure 3.* Top figure shows the simulator input “true” HLOS wind and the bottom shows the resultant L2B Rayleigh-clear HLOS wind observations (the resolution of the winds is indicated by the small rectangles). The colours indicate the HLOS wind value (m/s, see colour scale).
Figure 4 shows the L2B Mie-clear HLOS wind results for the same scenario. The complementary nature of the Rayleigh and Mie wind is shown in that the Rayleigh-channel gaps are partially covered by the Mie winds. Mie winds are very good quality at the top of optically thick clouds (due to the large backscatter). This complete profile coverage and the quality of the winds are encouraging for NWP use. Of course the across-track horizontal coverage is limited for Aeolus in the tropics (spaced by ~2500 km at equator), but the hope is that the data assimilation still can extract a lot of information from these continuous 2D slices of wind information.

![Figure 4](image)

*Figure 4. Similar to Figure 3 but for the Mie-cloudy L2B HLOS wind observations.*

The verification of HLOS winds from such simulation scenarios gives an indication of the potential L2B HLOS wind accuracy. Such verification has led to the identification of processing errors and hence improvements in the processing chain, which is a great boon when preparing for future real data. Statistics of the HLOS wind errors are given in Figure 4 for a scenario with ECMWF T1279 (~16 km grid) meteorological fields as input to the simulator. The observation minus truth statistics (with truth defined as the point-wind in the centre of the observation and not the averaged wind over an Aeolus cell) indicates that random errors are typically between 1.5-3 m/s standard deviation. As expected, the Mie winds are of superior quality, but the Rayleigh winds have much greater vertical coverage. Note that some quality control of the observations was necessary to produce these statistics because occasional outliers can ruin the standard deviation. The QC used the L2B estimated error provided with each wind, therefore this is a fair QC of the data i.e. similar thing can be done with real Aeolus data (e.g. removing estimated errors greater than 5 m/s for Rayleigh).

The systematic errors are by some measures larger than ESA’s specification for the Rayleigh; however a significant contribution to this bias is now understood and a correction will be soon included in the L1B processing (for Dark Current in Memory Zone correction). Of course if the simulation is missing a key feature of Aeolus instrumentation (missing error source) or lacking atmospheric variability (a known issue with NWP models) then these simulation errors will be too optimistic; however we think they give a reasonable impression of the coverage and quality of the observations. One issue to be investigated more is the effect of errors in the calibration. In these simulations the calibration was ideal (i.e. noise sources were off); therefore more rigorous testing with noise sources on is important to understand systematic errors.
5. INVESTIGATION OF APPROPRIATE AVERAGING LENGTH

A small investigation into what horizontal averaging length is most appropriate for Aeolus observations was done using aircraft u-component wind data sampled every ~1 km along the flight path (Global Aircraft Data Set, GADS, which are believed to have small measurement errors e.g. < 1 m/s). The data along the cruise-level flight path was averaged with a box-car average at varying length-scales. Then Gaussian noise was added to the averaged wind result to represent the expected Aeolus instrument noise levels for the Rayleigh channel (which vary with average length as $d^{-1/2}$). The results showed that at 25 km horizontal averaging the Rayleigh wind noise (~4 m/s) was much larger than the typical wind field variability at that length-scale and hence the Rayleigh winds are too noisy to provide useful 25 km scale wind information. However, 100 km averaging (Rayleigh noise around 2 m/s) seems to be a more appropriate averaging scale given the wind variability seen at that scale. The Mie channel winds have sub-2 m/s random error down to ~10 km (shown with simulation verification); therefore it seems that Mie winds are more useful for mesoscale NWP than the Rayleigh winds. This investigation did not consider what the NWP model can represent, which is another issue to consider for data assimilation.

6. WIND IMPACT INVESTIGATION AT ECMWF

The work of this section is documented in full by A. Horányi et al. (2014). Here we can only give an outline of the experiments and results. The investigation involved running one month-long OSEs (Observation System Experiments) at ECMWF, experimenting with the available in situ observations of wind and mass from aircraft; radiosondes and wind profilers.

Forecast impact was assessed with different combinations of wind and mass observations being assimilated (wind components, temperature and humidity). Questions such as “Which combination gives most impact relative to current Observing System?” were investigated. The satellite observing system and other conventional observations remained the same as the operational set-up for the control run.
Experiments were run where the wind observations are assimilated as Aeolus-like HLOS winds by converting the vector winds to HLOS wind component. These studies provided answers as to whether real observations of single-component winds (in a well observed system with operational ECMWF settings) can provide useful positive impact. Also which component of the wind gives most impact?

Also, experiments were completed where the observation error was artificially increased; both the random and separately the systematic errors, to see how the impact of the HLOS observations decreased. This is a relevant question for Aeolus given that there has been a decrease in the specified observation accuracy over the past few years (to allow laser pulse energy to be reduced, which reduced the risk of laser induced damage of the instrument).

Figure 6 summarises the results of the various OSEs in terms of the impact on ECMWF short-range forecast.

![Figure 6](image_url)

Figure 6. Results of a variety of OSEs assessing the impact of wind and mass data from in situ upper air observations and after various modifications. The impact is shown in terms of the reduction of vertically integrated total energy RMSE at 24 hr. forecast range (errors relative to operational analyses). The zero reference is without upper air in situ observations. 25%, 50% and 100% degradations refer to the increase of the specified observation random error standard deviation (with corresponding addition of Gaussian noise to the observations). The systematic errors (biases) are represented by adding constant offsets to the HLOS wind observations (with no account for the bias in the data assimilation system).

From the comparison of wind and mass impact, the wind was found to be more beneficial than mass (temperature and humidity) when added on top of the no upper-air obs control (more than twice the impact in terms of decrease of total energy forecast error, see Figure 6, particularly so in the Tropics). This is not surprising given that the satellite observing system is dominated by observations of the mass field i.e. the mass field is relatively well observed. It is reassuring to see that winds are as valuable as shown. Note that the impact of in situ vector winds gave a large impact in absolute terms (10% improvement as 24 hours in RMSE) and with strong statistical significance and positive impacts where sustained throughout the forecast range, even in the tropics.

For the experiments using HLOS wind observations: HLOS provides a large fraction of vector wind impact in ECMWF’s hybrid 4D-Var and EDA – which is very promising for Aeolus. The zonal
component impact is a bit larger than meridional, perhaps due to the kinetic energy of the atmosphere being mostly zonal (so it’s important to constrain this more).

For the experiments which degraded the quality of the HLOS observations, the increased random errors were not too damaging, which is also promising for Aeolus (if lower laser energy is needed). However a bias of 1 m/s leads to a worryingly large reduction in the Aeolus impact, a 2 m/s bias will wipe out any overall positive impact of the HLOS observations in the first place – therefore it is critical to minimise the Aeolus biases that we are unable to correct. We accept that these investigations have limited use for assessing the absolute impact of Aeolus (due to completely different observation coverage, resolution and differing error characteristics), but the relative changes in impact when altering the observations are important indications for the factors that affect NWP impact.

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