# Prospects for wind lidar assimilation

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**ABSTRACT**

The need for wind observations in NWP and their operational usage at ECMWF is discussed. The wind observation coverage continues to be highly variable, both horizontally and vertically, pointing to the need for more wind profiles to fill the gaps; the stratosphere appears to be particularly lacking in wind observations. One way to achieve this is through space-borne Doppler wind lidar (DWL). The measurement technique is described as are the prospects for a space-borne DWL, the first of which will be the ADM-Aeolus ESA Earth Explorer mission. Some properties of Aeolus are discussed e.g. error sources, sampling and how the observations are expected to look based on accurate simulations. Simulations show that the expected random errors are typically 2–3 m/s for the Rayleigh winds and 1–2 m/s for the Mie; work on improving the expected sources for systematic errors continues. Aeolus observations can provide unique vertical wind profiles from space, which is complementary to any existing observing system. Finally some thoughts on which Aeolus product to assimilate are given and some tentative expectations for the impact of Aeolus based on recent research from the community.

## 1 Wind observation usage in NWP

### 1.1 Introduction

Wind is a basic geophysical variable used in defining the state of the atmosphere for NWP. The assimilation of wind observations is the most direct way to improve the wind analysis. The wind observations used in global model data assimilation come typically from radiosondes, aircraft, wind profilers, screen level winds, scatterometer winds and Atmospheric Motion Vectors (AMVs). With multivariate data assimilation systems the wind analysis is determined not only by wind observations but also by other geophysical variables through balance constraints and by the model constraint (e.g. in 4D-Var). Talagrand (1981) showed that the wind field can be reconstructed from mass observations distributed in time, however it is more efficiently obtained using both mass and wind observations. Wind information can also be extracted by assimilating observations of tracers e.g. humidity in combination with the 4D-Var model constraint (e.g. Geer et al., 2014; Peubey and McNally, 2009). Multivariate analyses in 3D-Var rely only on diagnostic balance relations between the mass and the wind in the background error covariances, for mass observations to determine the wind and vice versa, however such relations can lead to poor estimates of the diagnosed variable (e.g. Randel, 1987).

Geostrophic adjustment theory (e.g. Haltiner and Williams, 1980) describes how a simplified, but realistic, model of the atmosphere returns to a state of geostrophic balance from an initially unbalanced state. The Rossby radius of deformation is a key parameter in determining whether the final balanced state is determined by the initial mass or wind state (or both). It is more important to know the initial wind state rather than the mass for the evolution of dynamical features smaller (in horizontal extent) than the Rossby radius and conversely the mass is important for larger horizontal scales. This suggests that analysis increments to the mass and wind state may be lost in the short-range forecast depending on their scale. However, the true atmosphere can be far from geostrophic balance and clearly it breaks down near the equator. Studies have shown that wind observations are more useful than mass for determining equatorial waves, see Žagar (2004).

In practice global NWP benefits from having a broad range of observation types distributed in time and space, providing redundancy in determining the complete initial state. The current GOS (global observing system) does not meet this need because of having many more mass observations than wind observations (see section 1.2). This is why the WMO (World Meteorological Organization) continues to state that wind profiles at all levels outside the main populated areas are the number one critical atmospheric variables that are not adequately measured by current or planned systems (see WMO, 2014).

## 1.2 Spatial distribution of assimilated wind observations

The spatial distribution and number of assimilated wind observations for a typical example ECMWF 12 hour analysis is shown in Figure 1 (from 00 UTC 1st June 2014 operational analysis). The wind observations are comprised of: aircraft 37%; scatterometer 23%; AMV 23%; radiosondes 12%; profilers 5% and ground based less than 1% (from a total of around 300 thousand observations).

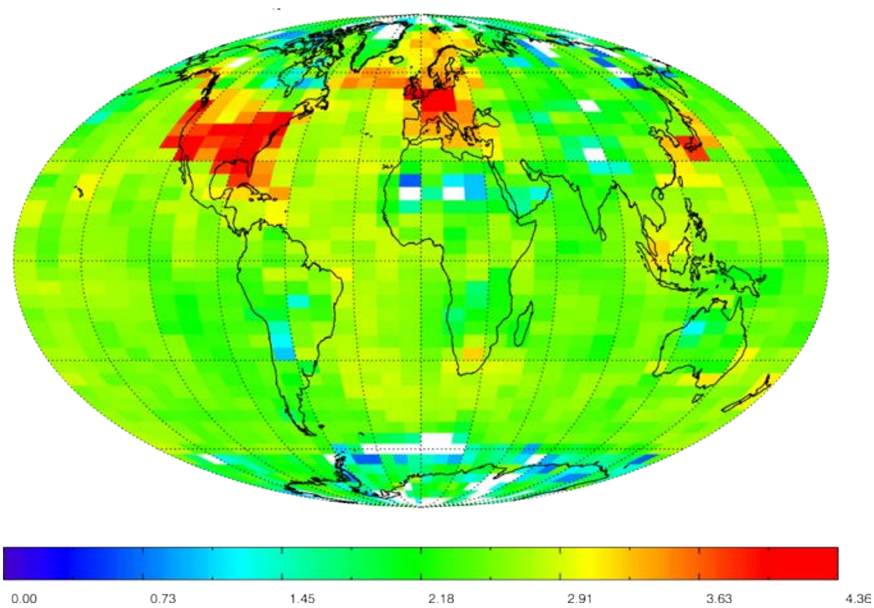



*Figure 1: Map of the number of wind observations assimilated per $10^6$ $km^2$ surface area within a 12 hour LWDA cycle at ECMWF. N.B. $log_{10}$ scale was required to see the details, due to the large range.*

There is great variability in the density of wind observations; with an order of magnitude more winds available over North America, Europe, North Atlantic and Japan compared to the rest of the Earth, due to aircraft winds (a log-scale was used to help cater for the large range of numbers). AMVs provide useful wind coverage on a near global scale; however the density assimilated is low due to thinning to mitigate correlated errors, hence why they are not clearly seen in Figure 1.

Figure 2 is the zonal average number of observations, as a function of pressure. Again the aircraft observations are dominant between 30-60°N up to around 200 hPa; aircraft observations occur at cruise level and during the ascent/descent near airports. The increased counts seen at specific levels in the NH (Northern Hemisphere) stratosphere are radiosondes reported on standard pressure levels. The tropics and SH (Southern Hemisphere) stratosphere is particularly lacking in wind observations. A band of increased numbers in the upper troposphere and lower troposphere at most latitudes are AMVs. The tropical upper troposphere and lower troposphere are relatively well sampled by AMVs (i.e. where there are many clouds), however the assigned (and actual) observation errors are large (see Figure 3) at 5–7 m/s, compared to ~2 m/s for in situ wind observations like radiosondes and aircraft winds. The larger assigned errors are to compensate for errors in the vertical geolocation of the AMV winds in high vertical wind shear regions and because clouds are dynamically evolving features.

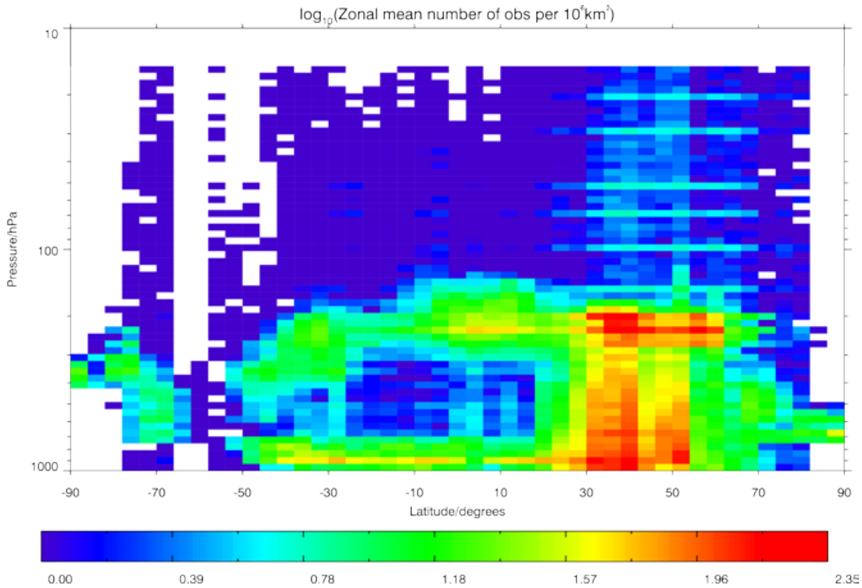



*Figure 2: Zonal average number of wind observations assimilated per$10^6$ km$^2$ area, per level within a 12-hour 4D-Var cycle at ECMWF. N.B. $log_{10}$ scale was used.*

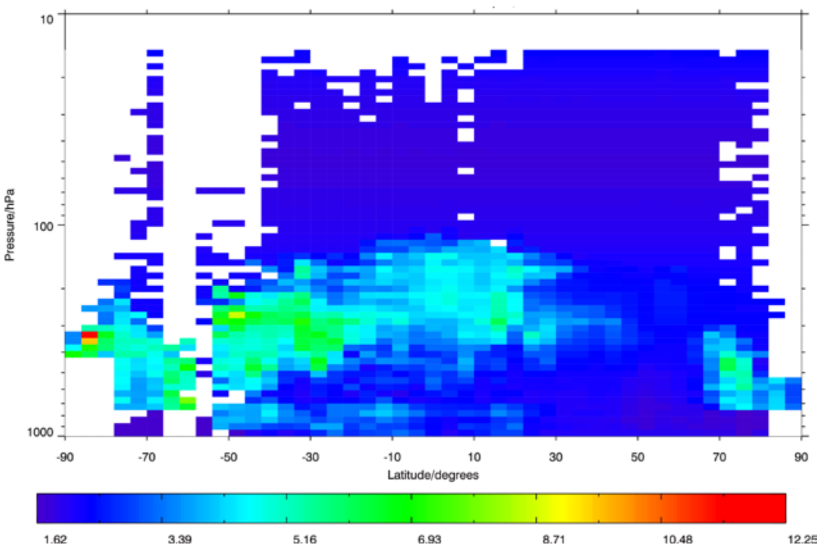



*Figure 3: Zonal average of the assigned observation error standard deviation (**R**) (units:m/s) within a 12-hour 4D-Var cycle at ECMWF. N.B. $log_{10}$ scale was used.*

To achieve a significant improvement in the accuracy of the wind analysis, then more wind profiles, preferably of a sufficient accuracy (say 2 m/s), are required in the tropics and SH and in ocean areas of the NH.

### 1.3 Accuracy of the background wind state at ECMWF

Given the distribution of assimilated wind observations, it is interesting to look at the accuracy of the ECMWF wind analysis (or the closely related short range forecasts). This was done for the January-September 2014 period by averaging the 12-hour forecast EDA (Ensemble of Data Assimilations, Isaksen et al., 2010) ensemble spread (standard deviation) for the zonal wind; this is an estimate of the average background forecast error standard deviation (this is before any calibration of the EDA spread; usually the ensemble is under-dispersive by 20–30%). A map of the average EDA spread for a model level near 300 hPa (upper troposphere) is shown in Figure 4. Generally the errors are largest in the tropics and over the oceans, and rather small towards the poles. Wind errors are also significantly smaller over the areas well observed by aircraft and radiosondes winds i.e. North America and Europe. The larger errors in the tropics are associated with the ITCZ. Direct wind observations are important for the tropical wind analysis (see section 1.1), and perhaps the lack of wind observations at mid-troposphere (in combination with model difficulties with convection) may explain the larger errors here. In a zonal average (not shown) the wind error maximum is found at ~150 hPa (upper troposphere) in the tropics. Figure 2 shows this region is sampled well by AMV wind observations, but the large observation errors and likely problems handling outflow from convection events correctly, may explain the disappointing impact.

The spatial patterns of error are similar to those of the differences between ECMWF and NCEP analyses as shown in Baker et al. (2014), Figure 2; suggesting that the background error spatial distribution is reliable.

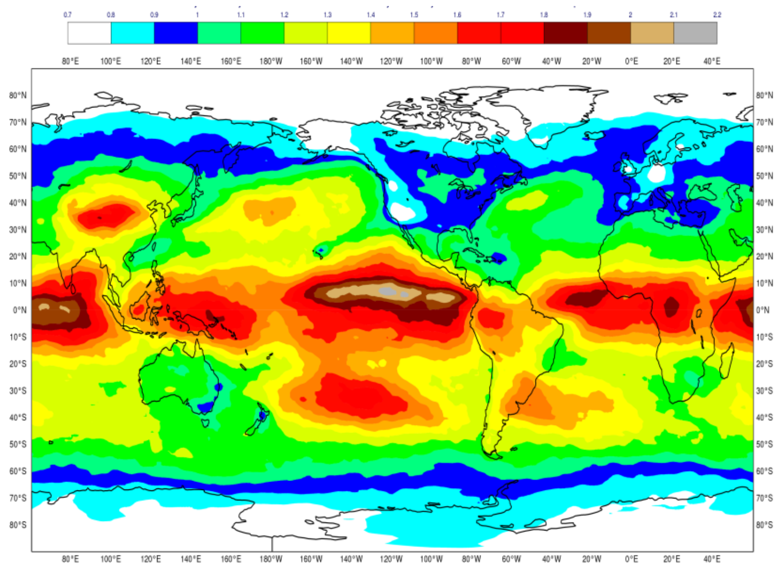


*Figure 4. ECMWF EDA ensmeble spread for u-component wind (m/s). Based on standard deviation of 12-hour (background) ensemble forecasts at 300 hPa averaged over the period January–September 2014.*

# 2 Doppler wind lidar

A promising observation technique to help fill gaps in the observing system is space-borne Doppler wind lidar (DWL). DWL measures vertical profiles of wind information with accuracies suitable for NWP. DWL has been well demonstrated through many aircraft and ground campaigns, however a space mission is yet to be realised.

## 2.1 Basic principle of DWL

A Doppler Wind Lidar (DWL) transmits laser pulses into the atmosphere and measures the frequency change of the backscattered light received, relative to the frequency emitted. The frequency shift occurs by the Doppler effect i.e. due to relative motion between the backscattering medium and receiver. A DWL aims to measure the Doppler shift due to the relative motion of the atmosphere above the Earth's surface i.e. the wind. Other sources of relative motion (e.g. receiver motion relative to Earth surface) are removed in the processing. The line-of-sight speed of the atmosphere (i.e. along the line-of-sight of the DWL laser) is linearly related to the measured frequency shift, providing a direct measurement of the wind in the measurement volume.

Backscatter from both atmospheric molecules (clear air, known as Rayleigh scattering) and atmospheric particulates (e.g. aerosol, hydrometeors, known as Mie scattering) can be used for determining the wind. For Rayleigh scattering, the Doppler shift occurs not only from the average motion of the molecules (i.e. the wind) but also from the molecules random thermal motion. This leads to a Doppler broadening with a Gaussian frequency spectrum (see Figure 5). With standard deviation of typically 280 m/s (proportional to square-root of temperature), this is a large effect compared to atmospheric wind speeds (maximum ~100 m/s). This is complicated further by Brillouin scattering (inelastic scattering off acoustic waves), which becomes important for higher atmospheric pressures. The frequency shift of the mean of the distribution is proportional to the wind speed (i.e. the spectrum of Figure 5 will shift along the abscissa by the Doppler effect of the wind).

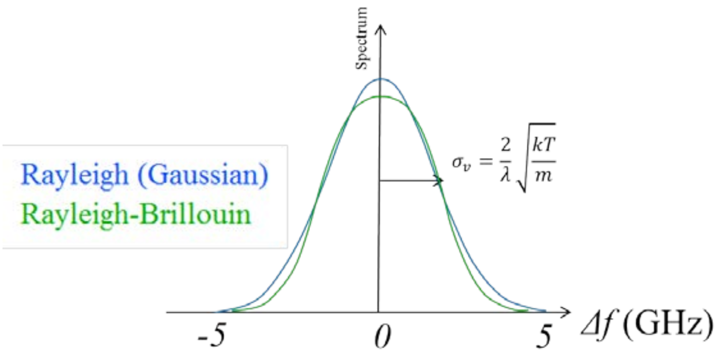



*Figure 5. Doppler broadened spectrum for Rayleigh scattering and an example of the effect of Rayleigh-Brillouin scattering.*

Atmospheric particulates have negligible Doppler broadening due to the larger mass of the particles; therefore the return bandwidth for the Mie spectrum is almost unchanged relative to the emitted laser i.e. narrow, making it possible for more accurate wind estimates than with the Rayleigh (given the same amount of backscatter). Similarly for particulate scattering, the shift in the frequency distribution mean gives the wind speed.

The higher the signal strength (i.e. the more photons received) the more accurately the true mean of the distribution can be estimated from the sample distribution i.e. the more accurately the wind can be determined. Therefore accuracy can be improved by increasing laser energy, receiving more backscatter from the atmosphere (e.g. denser atmosphere, or denser cloud/aerosol) or anything that makes the instrument detection more efficient. The determination of the frequency shift is typically done using spectrometers; details of the various methods can be found in e.g. Reitebuch (2012b).

## 2.2 DWL in practice

There are many examples of successful implementations of DWL both from the ground stations and from aircraft. NWP impact of DWL data from a relatively small aircraft campaign dataset was demonstrated by Weissmann and Cardinali (2007). Aircraft platform observations can be of very high accuracy due to the high laser energy possible, the close proximity to the atmosphere of the laser receiver and high horizontal resolution. A general disadvantage for DWL is that there is no transmission (and hence winds) below optically thick cloud, and also the swath is limited to the sub-platform "curtain". Determining wind from both methods of backscatter i.e. Mie and Rayleigh scattering provides a greater vertical coverage, but at the cost of more complicated instrumentation.

For space based DWL it is challenging to make robust enough instruments to operate for years without human intervention with sufficiently high laser energy to compensate for the large range (e.g. 400 km near-polar orbit altitude). Vector winds are not easily obtainable from a space DWL; but there have been proposals for multiple look missions (e.g. see presentations of the Working Group on Space-Based Lidar Winds http://cires.colorado.edu/events/lidarworkshop/LWG/ and Riishojgaard et al., 2012).

## 2.3 ADM-Aeolus mission

ADM-Aeolus is a space-based DWL technology demonstration mission. It is the second of ESA's (European Space Agency) Earth Explorer core missions. The objective is to demonstrate the ability to measure profiles of high-quality wind observations from the surface to 30 km (both Rayleigh and Mie scattering), using a DWL instrument in near-polar sun-synchronous orbit. Aeolus will measure horizontal line-of-sight wind components, perpendicular to the satellite track; therefore it is predominantly measuring the zonal wind component (and meridional as it approaches the polar regions). The mission is designed for a lifetime of three years. Aeolus has been significantly delayed due to technical issues with the UV laser (this wavelength enhances Rayleigh scattering, improving the clear-air winds). It is expected (at the time of writing) to be launched in 2016, because almost all of these issues have been resolved. Useful introductions to the mission and its instrumentation can be found in Reitebuch (2012a) and ESA (2008).

From ECMWF simulations it is estimated that in a 12 hour period, Aeolus should provide about 72 thousand winds that are of acceptable quality for data assimilation and distributed globally. This would be approximately a 11% increase in wind GOS.

## 2.4 Level-L2B HLOS wind product

The main Aeolus product expected to be used by NWP centres or researchers is the retrieved horizontal line-of-sight (HLOS) winds produced by the Level-2B processor (developed through collaboration between ECMWF, KNMI, Météo-France and DLR). The Level-2B (L2B) processor provides a retrieval of HLOS winds that are geolocated with geometric height as the vertical co-ordinate, with horizontal location, time and azimuth angle for each wind result. Each wind result also has an error estimate (which are found from simulations to be accurate estimates) and quality flags. Details of the algorithms of the L2B processor can be found in the L2B processor documentation (available from http://www.ecmwf.int/en/research/projects/aeolus). Briefly, the L2B processor provides:

- Flexible classification into wind types – cloudy or clear atmosphere.
- Flexible horizontal averaging of spectrometer counts, providing the user some control of noise and representativity of observations.
- Rayleigh winds corrected for temperature, pressure (which requires some a priori information) and Mie cross-talk.
- In a future release: estimates of optical properties (e.g. backscatter/extinction).

Many L2B processing options are controllable by the user. Given Aeolus is a research mission users are encouraged to run the L2B processor themselves and possibly improve the algorithms. The software is highly portable and is available free download from the web page specified above.

## 2.5 ADM-Aeolus simulations

ESA, the Level-1 and Level-2 processing teams have developed the software to realistically simulated Aeolus raw data, which can then be processed using the operational ground processing software chain. This is very useful for assessing the resultant L2B wind products and finding (and fixing) any problems in the simulation or operational processing chain.

The meteorological inputs to the Aeolus simulator (known as the E2S) are the truth against which we verify the L2B products. The simulation tool and processors have a plethora of options: the results described here are based on the default E2S noise settings and Level-1 processor settings. The L2B parameters have been tuned to get the best results.

Figure 6a shows the input truth optical properties as $\log_{10}$(scattering ratio) and Figure 6b the input truth HLOS wind, both as a function of altitude along the satellite ground-track. The scattering ratio highlights the clouds/aerosol backscatter relative to molecular backscatter. The optical properties i.e. backscatter and extinction profiles were derived from CALIPSO lidar observations by KNMI (Marseille et al., 2011). An alternative source of particulate optical properties is to forward model from the ECMWF clouds. Figure 6a labels the types of cloud and aerosol features encountered in this CALIPSO scene (the orbit path is courtesy of NASA, CALIPSO mission). The “true” HLOS wind in Figure 6b is the ECMWF model co-located to the CALIPSO data. The polar jet (5–10 km altitude), subtropical jet (6–15 km) and polar night jet (above 25 km) are encountered in this half-orbit scenario.

Figure 7 shows the retrieved L2B HLOS winds for both channels (Rayleigh (a) and Mie (b)), which can be compared to the “truth” HLOS wind in Figure 6b. The L2B Rayleigh and Mie-cloudy HLOS winds are somewhat noisy compared to the truth; however the accuracy is enough to be able to resolve the jet stream cross-sections well, given the near complete coverage from surface to 28 km in some regions. Such sampling of the wind field would be unique in global NWP.

a)

b)

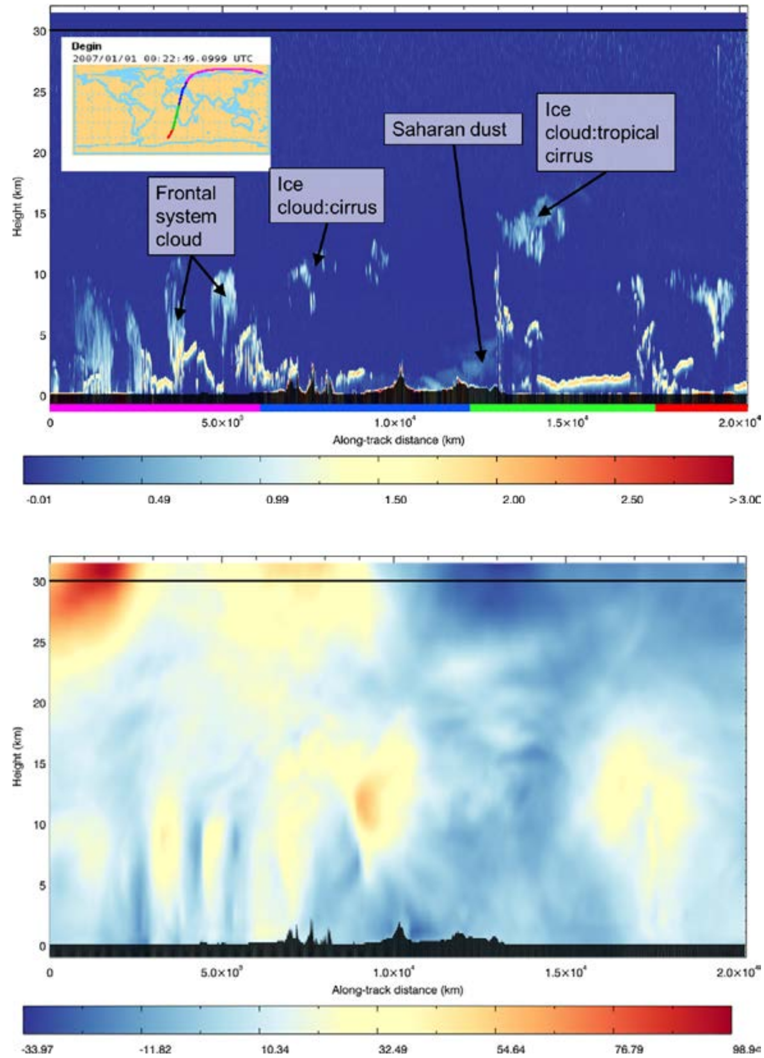
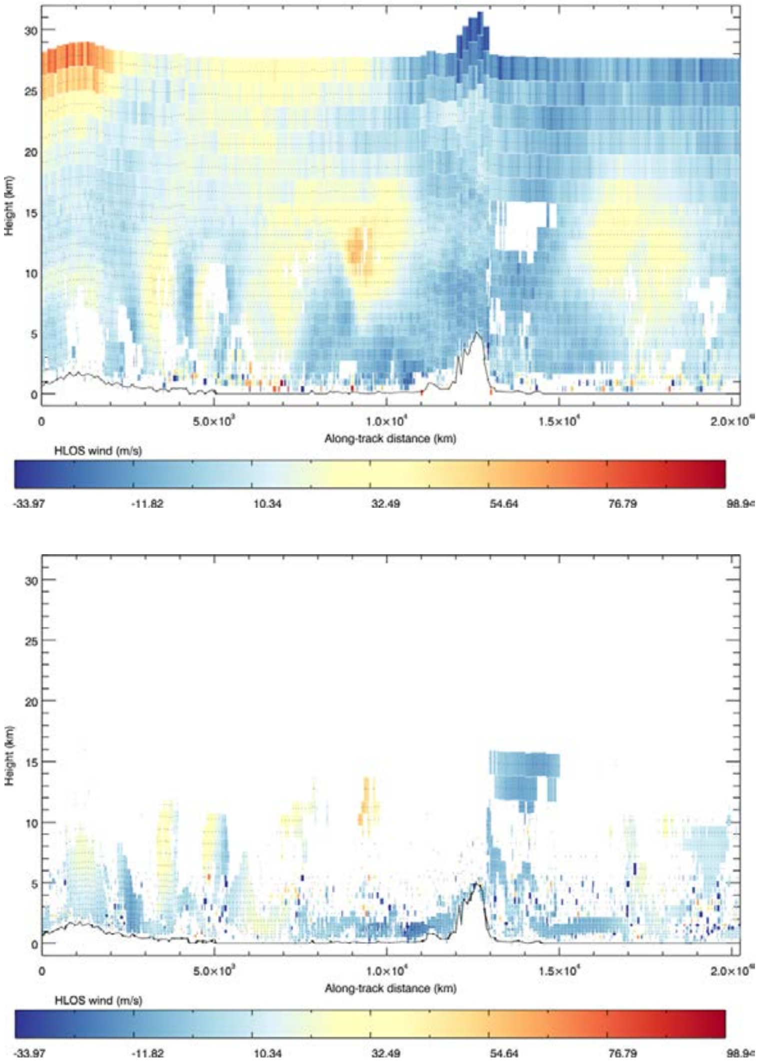



*Figure 6: a) The particulates of the scenario (derived from CALIPSO), as shown by the scattering ratio. b) The input HLOS wind information (i.e. "truth") units: m/s*

Error statistics (where error is defined as observation minus truth) were calculated, as shown by Figure 8 as a function of altitude. The example results are from a four orbit scenario using ECMWF cloud properties for cloud backscatter and extinction (which are found to appear realistic, scenario not shown here). Note that simulations with CALIPSO optical properties suggests that the bulk of Mie results are from cloud rather than aerosol backscatter. The laser pulse energy was set to the expected Aeolus setting of 80 mJ and the observations are constructed by averaging measurements horizontally up to the one so-called BRC (basic repeat cycle) level, which is around 90 km.



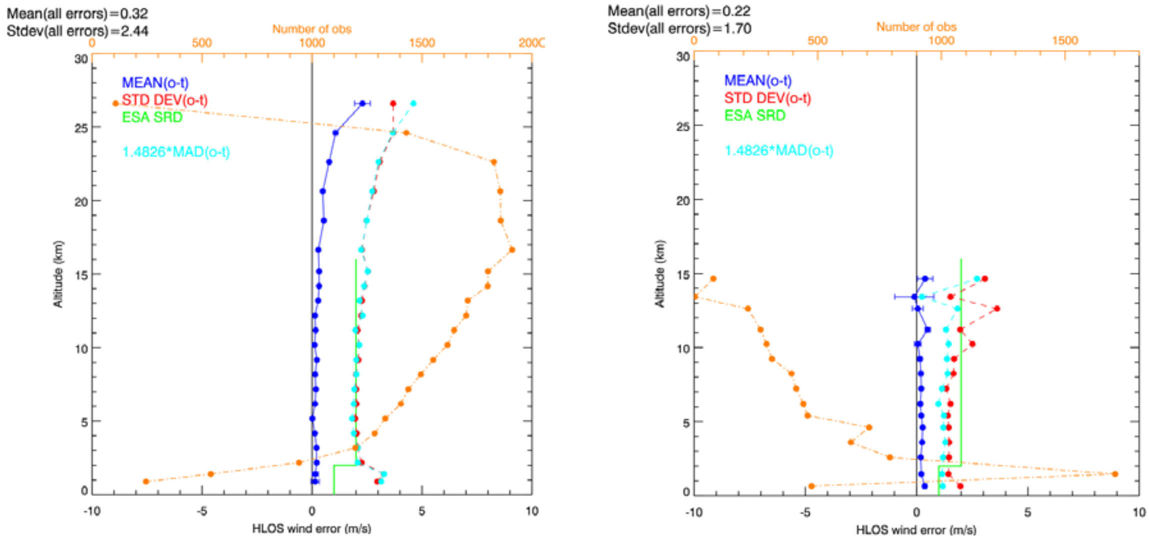

a)

b)

*Figure 7: Aeolus simulation L2B wind results: a) L2B Rayleigh-clear HLOS winds and b) L2B Mie-cloudy HLOS winds. Units are m/s, according to colour scale. These are all results, including outliers.*

The Rayleigh-clear wind errors of Figure 8a are biased typically less than 0.5 m/s and the standard deviation is 2–3 m/s. Quality control (QC) was necessary to ensure the error statistics are not ruined by a few gross error outliers. The QC is based on the L2B estimated HLOS wind error; results are rejected for estimated error greater than 5 m/s for the Rayleigh and 3 m/s for the Mie. This QC is a good compromise between accuracy and the number of results available. A cause of the bias is now understood and a correction in the L1B processing will be applied in upcoming versions. The Rayleigh-clear errors increase with altitude because of lower molecular backscatter signal in the stratosphere as density decreases exponentially with altitude. Close to the surface the errors are a little larger due to signal loss via thinner range-bins and signal attenuation by clouds. The number of observations (accepted by the QC) decreases below the maximum at 15 km to less than half that near the surface due to rejections, primarily due to lower signal levels as a result of clouds.

For the Mie-clear results (Figure 8b) the biases are less than 0.3 m/s and the standard deviation is 1–2 m/s. The observation count peaks in the first few kilometres altitude (reaching a level just less than the peak of the Rayleigh-clear results) thanks to low level clouds. The Mie winds account for 19% of the total number. Note that the error statistics remain stable with different "realistic" simulation scenarios.




a) b)

*Figure 8: Error statistics for a) L2B Rayleigh-clear HLOS winds and b) L2B Mie-cloudy HLOS winds.*

## 2.6 Error sources for ADM-Aeolus

Having sufficiently small observation errors (both random and systematic) is critical for Aeolus to provide a significant positive impact in NWP, and hence prove Aeolus to be a useful demonstration mission. The ECMWF zonal wind background error is typically 1–4 m/s, therefore Aeolus random error should preferably be a similar magnitude to provide significant information to the analysis.

The random errors affecting the Aeolus instrument are:

- Readout noise, dark-current noise, laser frequency stability
- Pointing/spectrometer alignment errors. Can be improved by ground returns, which act as zero wind reference. The spectrometers are sensitive to the angle of incidence of the returned light, therefore any sources of angular variation need to be calibrated. Also errors in angular pointing knowledge mean errors in the ability to correct the satellite relative velocity, which is very large compared to atmospheric winds.

Also, Aeolus has what could be referred to as unwanted signals which can degrade the determination of the wind:

- Aeolus measures photon counts from interferometers. The photon counting process is subject to shot noise, which follows Poisson statistics with $SNR \propto \sqrt{N}$ . Shot noise is thought to be the main error source for Aeolus.
- Solar background light. Imperfect correction leaves some errors.

- Sampling error: wind/backscatter variability across measurement volume. This is not easy to simulate i.e. small-scale atmospheric turbulence. Airborne campaigns suggest this could be a significant error source (can interact with angular sensitivity).
- Vertical wind aliased onto horizontal wind. LOS wind speed is converted (user choice) to HLOS wind speed with the assumption that the vertical wind speed is zero.
- Imperfect Rayleigh wind retrievals due to imperfect corrections for temperature, pressure and Mie-cross talk effects.

If such errors occur in calibration, then systematic errors can result.

Aeolus emits laser pulses continuously into the atmosphere. From the discussion above it is evident that laser pulse energy is very important for the wind quality. The signal received from one laser pulse is too noisy to retrieve winds, therefore it is necessary to accumulate signal over many pulses to get accuracy of order 2 m/s HLOS (a level specified by ESA for the system requirements). The spectrometer counts from each pulse are averaged on board the instrument to produce a so-called measurement. A measurement (current definition) consists of 20 pulses, and so with a satellite ground-track velocity of around 7.21 m/s, each pulse is separated by 144 m. The measurement is therefore 2.88 km in horizontal extent. In the vertical dimension, each range-gate is 0.25–2 km thick; this is an on-board accumulation of signal (note that the 24 available range-gate thicknesses are configurable). The measurements can be further horizontally averaged in ground processing up to a so-called observation – typically an observation can be 30 measurements (~86 km), however L2B processing is flexible in this respect.

Given the satellite motion, the measurements are averaged across a varying atmospheric scene, i.e. small-scale wind variability is averaged which should make observations which are more representative for global NWP models. Less horizontal averaging is required for the Mie compared to the Rayleigh to achieve a given accuracy, as shown with the simulation error statistics in Figure 9. The simulation used the ECMWF T1279 meteorological fields sampled every 16 km. The sharp increase in Rayleigh wind error at scales less than 80 km is due to shot-noise.

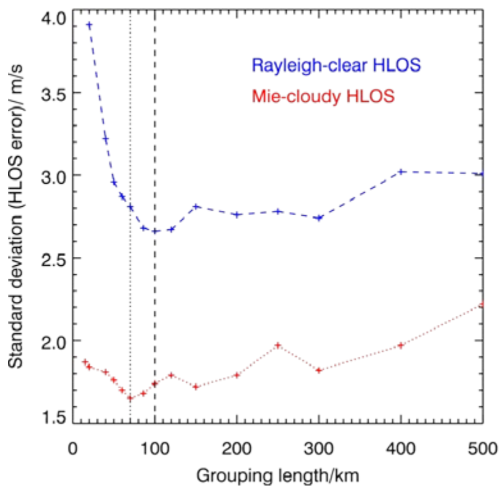



*Figure 9: The variation in HLOS wind error (profile average) standard deviation as a function of observation averaging length from a simulation with ECMWF T1279 fields as input.*

The Mie winds potentially have more extreme representativeness issues due to the spatial variability of the backscatter source i.e. cloud/aerosol. Therefore the wind could represent a narrow cloud layer with limited horizontal extent (therefore making it more like a point wind); also the 0.25-2 km range-bins mean that the vertical placement of the wind can be incorrect up to 1 km which is a problem in strong wind shear regions.

## 2.7 What level product to assimilate?

As with all remotely sensed data a decision has to be made as to what level of observation product to assimilate (Eyre, 1997). For Aeolus the best compromise between the "rawer" observations (requiring complex forward models) and a retrieved geophysical variable (requiring more processing assumptions and a priori information) was decided by the Aeolus science teams to be the L2B HLOS wind. The forward model chosen at ECMWF to assimilate L2B HLOS wind is very simple and has been explained in Tan (2008); note for NWP models with vertical wind speed in the control vector, the LOS rather than HLOS wind could be used. Figure 10 summarises the possibilities for Aeolus assimilation and how the current preferred choice, i.e. L2B HLOS wind, fits in.

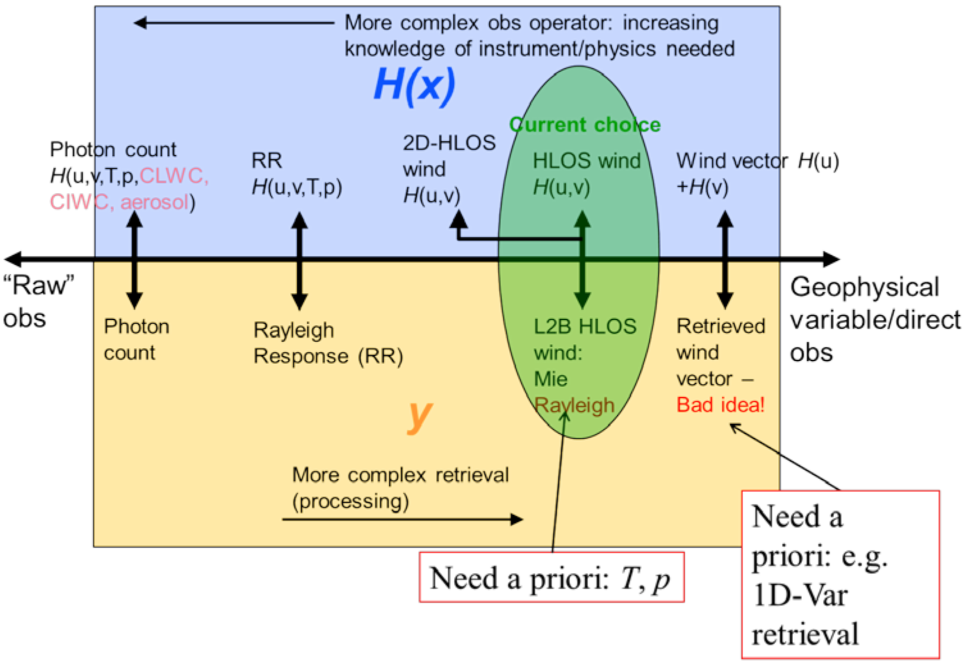



*Figure 10: A visualisation of the possible choices for which level of Aeolus product to assimilate in NWP.*

An extended retrieval to obtain a geophysical variable closer to the control vector e.g. vector wind, is possible, but this would rely significantly upon a priori model information (i.e. model wind vector profiles), which may give negative impact due to observation errors being correlated with background errors. Note that the L2B Rayleigh winds requires a priori temperature ($T$) and pressure ($p$) information for a correction; however the sensitivity of wind errors to $p$, $T$ errors is small, which justifies its choice for assimilation. The Mie HLOS winds are independent of a priori model fields.

For Rayleigh winds, to avoid issues with a priori $p$,$T$ information, the so-called Rayleigh response (RR) could be assimilated, with a forward model depending on wind, $p$ and $T$. An issue with RR is that is not a geophysical variable, and hence it depends on the instrument characteristics which will change, making forward model maintenance more difficult. Also Tan (2008) explains a method to add *T*, *p* dependence to the Rayleigh HLOS forward model.

Going to even rawer products like spectrometer counts may have a benefit in that there is not only information from Doppler effects: wind (and *T*, *p* for Rayleigh) but also from signal amplitudes: molecular and particulate concentrations (i.e. *T*, *p* and cloud/aerosol properties). Instrument knowledge, forward model complexity and issues assimilating cloud/aerosol probably prohibit this choice for today's NWP systems. The amplitude information is however exploited in a separate L2A product of optical properties retrievals (which may be useful for the Copernicus Atmospheric Monitoring Services).

## 2.8 Some expectations for ADM-Aeolus NWP impact

Three recent investigations that are useful for assessing Aeolus' potential NWP impact will be discussed in this section.

The first is the ESA funded research study which used the EDA (Ensemble of Data Assimilations) method to assess the potential impact of Aeolus observations. Simulated Aeolus HLOS wind observations were assimilated in the ECMWF EDA system (Megner et al., 2013). When adding the new simulated observation type, a reduction (or increase) in ensemble spread can be interpreted as positive (or negative) impact of the new data on the analysis or short-range forecast skill (the method was developed by Tan et al., 2007). This method combines the real observing system with some simulated observations allowing for some calibration of the spread change against that for real observations. The Aeolus simulated observations were produced by an accurate simulation (at least in terms of random errors) using Met Office analyses as input to the simulation. The EDA members were run at T399 resolution; this may have limited the wind observation impact which is expected to be more important for small scales (see Section 1.1).

The results indicated Aeolus' impact on the zonal wind short-range forecast was similar to that of the radiosonde network (removing the real radiosonde data was used as a calibration for the impact). The impact was largest at ~200 hPa, particularly for tropical ocean areas and for the winter polar regions. Typically improvements in zonal wind were found to be ~5 % at short-range; such improvement could lead to 1–3 hours improvement in forecast skill based on empirical error growth curves.

The second study of interest was an OSSE performed at JCSDA using the NCEP GSI/GFS system with a 2009 setup (Zaizhong et al., 2013, earlier studies using the same system are described in Riishojgaard et al., 2012 ). Several possible DWL satellite configurations were tested (great effort was taken in the OSSEs to ensure realistic simulation of the DWLs). The impact in the NH for 500 hPa geopotential height was around 5 hours for a four-look DWL and ~1 hour for a 1-look (like ADM-Aeolus). In the SH the impact was 6 hours for a 4-look DWL and 3 hours for a 1-look DWL (like ADM-Aeolus). Largest impact (at least for short forecast ranges) was found on the tropical winds with an impressive 15% reduction in RMSE (for a 1-look DWL) at 200 hPa.

The third study involved running OSEs using the ECMWF system to investigate the impact of wind using in situ wind observations (Horányi et al., 2014). A baseline experiment was set-up in which all the in situ observations were removed (but the satellite observing system remained). The wind observations from aircraft; radiosondes; PILOT and wind profilers are then put back into the system after conversion to Aeolus-like HLOS winds. The HLOS wind observations (constructed from real vector wind observations) were found to give very useful impact: they provided around 70% impact of the vector wind observations (zonal gave more impact than meridional), showing that a modern data assimilation method can use HLOS data effectively, which is promising for Aeolus. Also, some comparisons showed that the wind information from the conventional data was much more useful than the mass, especially in the tropics (partly because the mass field is already well observed by satellites). The typical impact of the zonal HLOS winds was found to be 2–5 hours in NH extratropics. There were large impacts in tropics despite very few in situ wind observations. Of course by taking out the conventional data (i.e. a lower quality analysis) and the fact that the observations have very different sampling properties to Aeolus means that the impact is hard to extrapolate to Aeolus impact, but it confirms the importance of accurate wind observations.

Very tentatively one can make some predictions for Aeolus' impact. If the mission error specifications are met, then in the SH extratropics the 500 hPa geopotential may be expected to improve by ~3 hours, 2–5% analysis improvement. The NH extratropics geopotential height improvement will probably be smaller. Similar predictions apply for extratropical winds. It is increasingly difficult for any one observation type to show "large" impact when assimilated on top of full OS. This was demonstrated by ECMWF OSEs shown in the 2014 ECMWF Seminar (McNally, 2014). In the tropics there is evidence that locally large impacts could occur, e.g. up to 15% improvement in upper tropospheric winds at short range, which is a considerable improvement. Of course real data may have numerous issues that not yet considered, after all Aeolus will be the first DWL in space, therefore these are only estimates.

## 3 Outlook

DWL wind observations have the potential to provide very useful improvements in global NWP analyses, particularly in the tropics. The realisation of this will have to wait for the first space-borne DWL mission i.e. ADM-Aeolus, to be launched in 2016, if all goes well. ECMWF will be well prepared to use the data operationally if it meets the required accuracy, and the L2B processing software to produce products for assimilation will be available for NWP centres and researchers.

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