Assessment of the Impact of Aeolus Doppler Wind Lidar Observations for Use in Numerical Weather Prediction at ECMWF

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by Michael Rennie and Lars Isaksen
ESA-ESRIN produce Level-1B data (calibrated signal levels)

**Level-2B wind product** (suited for Numerical Weather Prediction (NWP)); produced by ECMWF

ECWMF data assimilation analysis

- **From 12 May 2020 (TBC):** L2B BUFR from ECMWF to EUMETSAT for distribution on GTS/EUMETCast (public data release)

L0 and L1A data

L1B — L2B — L2C

L2A

ESA-ESRIN produce L2A (optical properties) product

Wind products available in NRT for benefit of NWP
Examples of Aeolus Level-2B horizontal line-of-sight (HLOS) winds
Aeolus HLOS winds are positive if wind blowing away from satellite.
Aeolus L2B Rayleigh-clear and Mie-cloudy HLOS winds (1 orbit)

10/2/2020

Descending orbit phase

Ascending orbit phase

Polar-night jet (westerlies)

Subtropical jet (westerlies)

Polar front jet (westerlies)

Mountains

Varying range-bin settings
A very windy day in north-west Europe (10/3/2019)

Photo from my garden near Reading: apart from low level clouds, sky was clear

What Aeolus observed (Rayleigh + Mie winds) near the low polar front jet
Rayleigh and Mie winds are complimentary

Mie-cloudy L2B HLOS winds

Rayleigh-clear L2B HLOS winds

~12 km horizontal averages

~80 km horizontal averages
Aeolus use in NWP at ECMWF
Aeolus use in global Numerical Weather Prediction at ECMWF

• We have demonstrated positive impact in Observing System Experiments (OSEs) for three different periods
  – However, magnitude of the impact is smaller than hoped for pre-launch, due to:
    • **Data quality is not as good as expected** pre-launch i.e. noisier winds, larger biases than expected
    • Larger noise is an instrumental issue that *on ground processing* cannot resolve (lower laser energy than expected and unexpected signal loss in receive path)
    • **Have developed a bias correction scheme for Aeolus as part of the ECMWF data assimilation system to allow use in operations – since 20th April 2020 this no longer needed**
  • But **NWP impact is still good** for one instrument on one satellite, compared to other satellite instruments
  • Hence Aeolus Level-2B HLOS wind was **operationally assimilated since 9th January 2020**
  • Other NWP centres, such as DWD, Met Office, Météo-France, US agencies are also showing positive impact from Aeolus
L2B HLOS (horizontal line-of-sight) wind data assimilation

- **ECMWF Observation operator**: HLOS wind operator (point-wind version)
  - Interpolation of model wind \((u,v)\) to obs geolocation point
  - Calculate HLOS wind from model \((u,v)\)
  - Dot product of wind vector with laser pointing unit vector

\[ v_{\text{HLOS}} = -usin\phi - vcos\phi \]

\(\phi=\text{azimuth angle of line-of-sight}\)

- **Weaknesses**:
  - HLOS wind assumed to be a “point” observation rather than actual spatial average
    - However ECMWF model effective resolution is 4-8 times the grid spacing (~36-72 km horizontally), so may not matter
    - Probably more important to consider the Aeolus’ vertical averaging
  - Ignores vertical wind component \(w\) (should be close to zero over e.g. 80 km averaging, but may be important in certain conditions e.g. convection, gravity waves)
  - L2B **Rayleigh** wind retrieval uses a priori knowledge of \(T, p\) (a small dependence on ECMWF model) due to Doppler broadening, but is not important compared to other errors sources

- **Assigned observation error** is a function of the L2B processor estimated instrument error – now being refined to include representativeness error for Mie
Global HLOS wind O-B departure statistics for L2B Rayleigh-clear, 10 orbits on 21/1/20

- Global average bias is reasonable
- Robust st. dev. (O-B):
  - Profile average = 5.95 m/s
  - At 5 km = 5 m/s
- Estimated observation error from O-B departures
  \[ \sqrt{\text{st. dev.} (O - B)^2 - \sigma_B^2} \]
  - Profile average = 5.6 m/s
  - At 5 km = 4.6 m/s
  - Larger than we hoped for before launch
- Radiosonde has stdev(O-B) around 2 m/s
With worst case solar background noise.

Doubling useful signal would massively improve Rayleigh winds!

Given our current useful signal versus solar background noise we have a lot to gain from more useful signal, particularly in polar summer conditions.

A simulation, but tuned to actual L2B Rayleigh-clear random errors found:

- With typical solar background noise:
  - 7 m/s
  - 4 m/s
  - 3.9 m/s
  - 2.7 m/s

Typical useful signal level for 14 km altitude 1 km range-bin.
Global HLOS O-B statistics for **L2B Mie-cloudy**, 10 orbits on 21/1/20

- Global average bias is reasonable and stable with time
- Global average robust std. dev. (O-B):
  - Profile average = **4.2 m/s**
  - At 1-2 km ~ **3.5 m/s**

- Estimated observation random error from O-B departures
  \[ \sqrt{\text{st. dev}(O - B)^2 - \sigma_B^2} \]
  - Profile average = **3.7 m/s**
  - At 1-2 km = **2.9 m/s**
- Mie averaging length scale is \( \leq 14 \) km
  (Rayleigh is \( \leq \sim 84 \) km)
- Mie noise better despite much better horizontal resolution than Rayleigh
Long term trends in quality of operationally produced Level 2B winds

Rayleigh-clear; global, whole profile

Relaxed QC: $|O - B| > 15 \text{ m/s}$ rejected
Mie-cloudy; global, whole profile

QC: $|O - B| > 10 \text{ m/s}$ rejected
A major breakthrough in Autumn 2019: explanation was found for dominant source of Rayleigh wind bias which varies on less than one orbit time-scales

- Investigations showed Rayleigh wind bias, which varies along the orbit, is strongly correlated with the ALADIN telescope primary mirror temperature variations
- Temperatures vary due to varying Earthshine and the mirror’s thermal control
  - Temperature variations correlate with outgoing SW and LW radiation
- **Mechanism**: thermal variations alter primary mirror shape, causing angular changes of light onto spectrometer, causing apparent frequency changes
- **Bias correction** using measured telescope primary mirror temperatures was demonstrated to work in offline testing and was implemented in operations on 20 April 2020
Rayleigh has large biases which vary with geolocation

Ascending orbit phase e.g. 6/8/2019 to 7/9/2019

Descending orbit phase

Average M1 telescope mirror temperature
Plot from F. Weiler (DLR)

M1 mirror Ø 1.5 m
Regression of $<\text{O-B}>$ versus M1 temperature function
Best results on 8/8/19 obtained with:
Outer temp. average: AHT-27, TC-20, TC-21
Inner temp. average: AHT-24, AHT-25, AHT-26, TC-18, TC-19

$y = 47.127x + 10.489$
$R^2 = 0.9325$

15 m/s HLOS range!

Demonstrates the power of NWP models for helping to determine the source of errors in observations
Example of bias correction

Rayleigh bias versus time on **9/8/19**

- Before bias correction
- After M1 temperature bias correction using 8/8/19 regression
- arg_lat and long corr to model (haa2)

\[ \text{stddev}(\langle O-B \rangle) : \]
- 2.62 m/s
- 1.05 m/s
- 0.76 m/s
Effect of M1 temp. bias correction (new L2B processor) on Rayleigh data for 5/4/20

- Global robust stdev(O-B) improved by ~0.6 m/s
- Global bias of -3.5 m/s removed

Bias versus argument of latitude (orbit phase angle) removed
Assessment of Aeolus NWP impact at ECMWF

- **Observing System Experiments**
- Three periods have been investigated so far
  1. September 12\textsuperscript{th} to October 16\textsuperscript{th} 2018 (**early FM-A (first laser)**)
  2. April to June 2019 (**end of FM-A period**)
  3. **Focus today on:** August to December 2019 (**FM-B (second laser)**)
NWP impact of Aeolus with FM-B laser – August 2\textsuperscript{nd} until 31\textsuperscript{st} December 2019

• Experiments with operational Level-2B data, and full observing system for other data

• $T_{CO399}$ (~29 km model grid)

• Test data used \textbf{does not have M1 bias correction}, therefore \textbf{apply bias correction to ECMWF model wind as function of “orbit phase angle” and longitude}

• Assigned observation errors use L2Bp instrument noise error estimates
  – Simple model: multiplicative factor to get more agreement with Desrozier diagnostics
Bias correction using the ECMWF model as a reference

- Implemented bias correction scheme: \(O-B\) vs. “orbit’s argument of latitude” and longitude; look-up table
- Updates to bias correction look-up table done every few days in experiments
- Mie biases stable with time and do not require the longitude dimension

Example of how Rayleigh biases varied during the FM-B period

M1 temperature induced biases were larger in N. hemi. summer
Changes in the u-wind analysis at 250 hPa (~10 km) due to assimilating Aeolus Rayleigh-clear+Mie-cloudy winds (for August to October 2019)

Largest changes made in the tropical upper troposphere and SH extratropical cyclone development areas over the ocean.
Mean change in analysis u-wind at 150 hPa (~15 km) due to Aeolus – suggests Aeolus is correcting model biases here.
Background fit to other observations when assimilating Aeolus (Rayleigh-clear + Mie-cloudy) – results of OSE (for period 2/8/19 to 31/12/19)

Conventional vector wind observations i.e. aircraft, radiosondes, wind profilers

N. Hemi. extratropics  tropics  S. Hemi. extratropics

Better with Aeolus if < 100%

Aeolus impact best in the tropical upper troposphere
Background fit to other observations when assimilating Aeolus

Important MW and temperature/humidity sensitive data

Aeolus is improving wind, temperature and humidity
Vector wind root mean square error impact of Aeolus (Rayleigh-clear + Mie-cloudy)

- Positive impact is strongest in the tropical upper troposphere and polar troposphere; at day two forecast range
- Longer range negative impact at upper levels in the SH is negative seems to be sensitive to weight given to Mie winds
- Similar impact patterns are seen for temperature and humidity forecasts
Another metric: Zonal average view of Aeolus Forecast Sensitivity Observation Impact (FSOI) – short range forecast impact on global dry energy norm

**Results from operational assimilation**

Zonal average Rayleigh-clear FSOI

- Rayleigh has smaller magnitude impacts than Mie, but more consistently positive, with a larger impact in the tropical upper troposphere – agrees with OSEs

Zonal average Mie-cloudy FSOI

- Mie has bigger magnitudes but more mixed positive/negative – it is thought that better modelling of observation errors will improve this
Global relative FSOI split by instrument types

Aeolus does well

Good for one satellite

Global FSOI per observation

Aircraft obs
Recent results – **Mie impact can be increased** with improved assignment of observation error (including representativeness error)

**Mie-only impact** on vector wind for 2 August to 26 December 2019

Observation errors as in current operations at ECMWF

Improved Mie observation error model

- **T+48**

Better with Mie

-4%  
+4%
Summary of Aeolus NWP impact assessment at ECMWF (so far!)

• Aeolus impact assessment
  – OSEs have shown statistically significant positive impact in tropics and at poles
  – FSOI from operations shows Aeolus is a useful contribution to Global Observing System
    • Shows **benefit of direct winds**
  – Aeolus is only <1% by number of obs assimilated (more wind profilers needed)
  – Rayleigh winds are providing most of the tropical impact (OSE and FSOI agree), but Mie impact is improved by more realistic observation error modelling
  – Early FM-B (with more signal) shows larger impact than in late FM-A period
    • Smaller wind errors hence more weight in data assimilation
    • Suggests if we could somehow get back some of the missing factor 2-3 of photon counts, **impact would be much greater, especially when solar background noise is large**
    • Good impact had relied on bias correction using the model as a reference (particularly for Rayleigh channel)
    • However upcoming operational processor (telescope temperature dependent bias correction) reduces the model reliance
  – **There is still plenty of scope to improve the impact, both in processing the observations and in the assimilation methods**