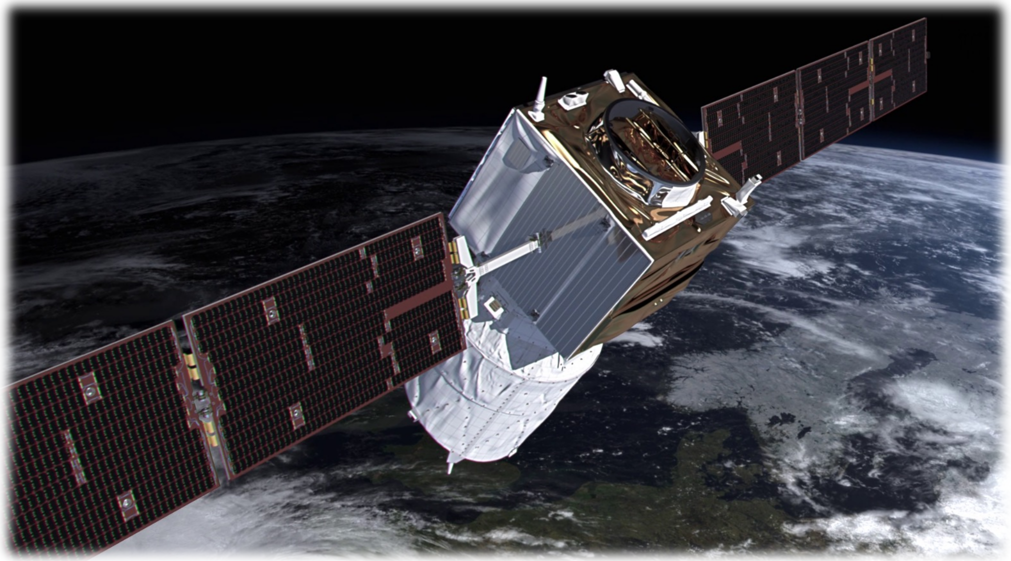
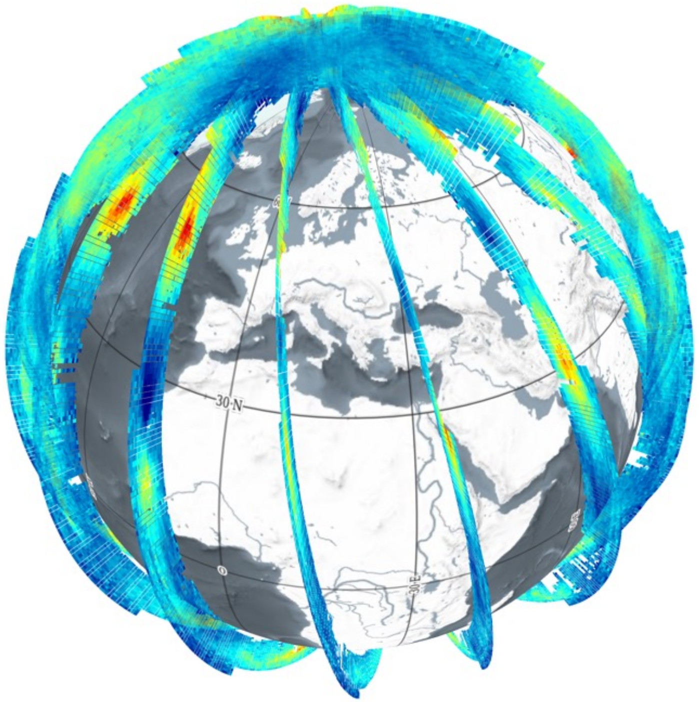
Wind information from Aeolus

EUMETSAT/ECMWF NWP-SAF Satellite data assimilation training course, 2023

by Michael Rennie* (m.rennie@ecmwf.int)

Many thanks to colleagues from ECMWF, ESA, Aeolus DISC and particularly DLR for providing material





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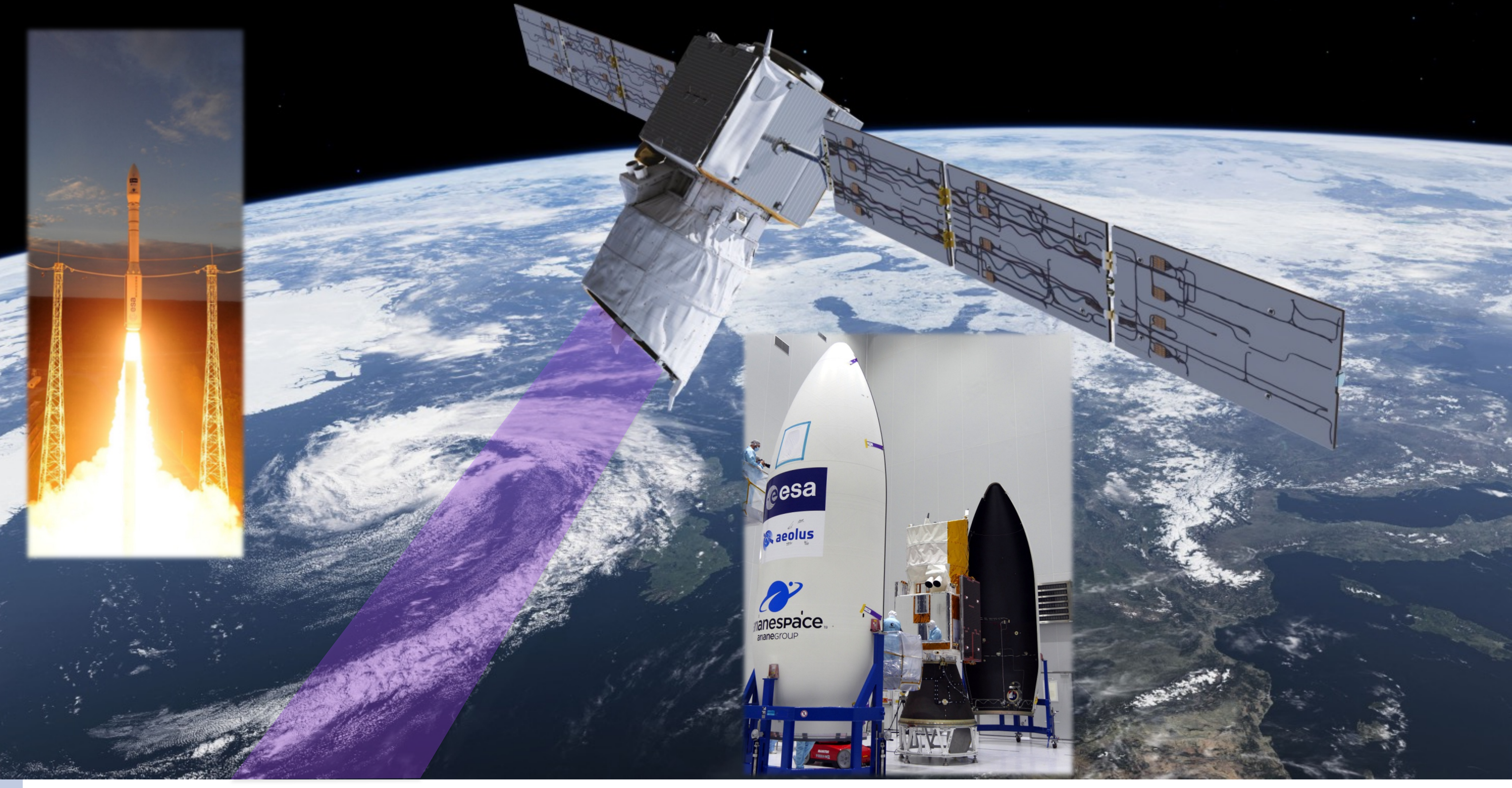
ECMWF

esa
European Space Agency

aeolus

DISC

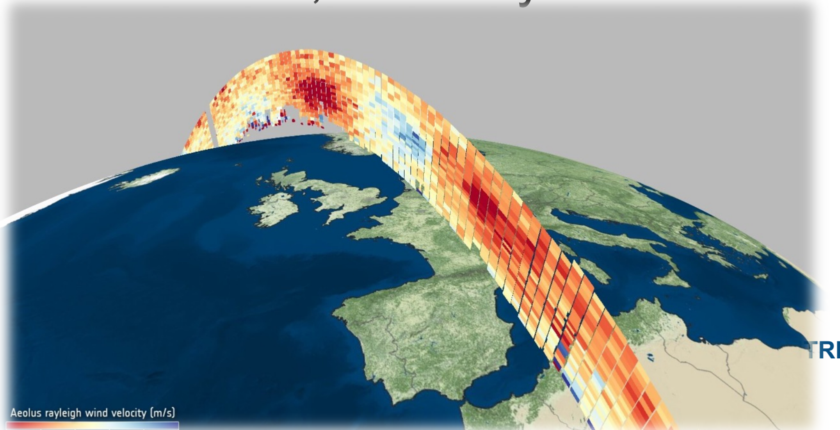
An introduction to Aeolus

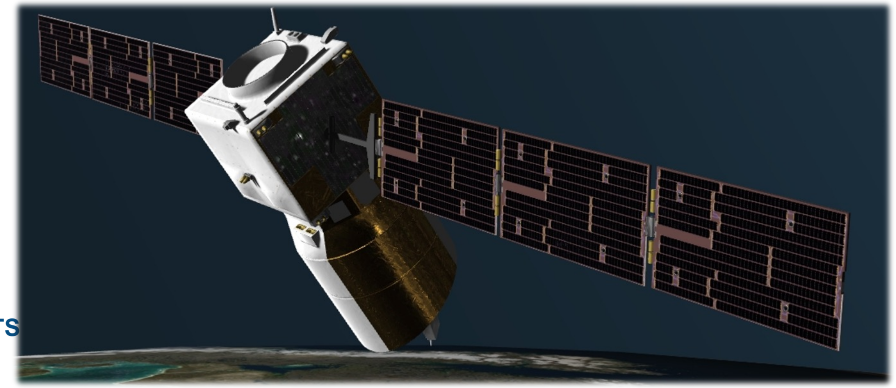


Aeolus satellite mission

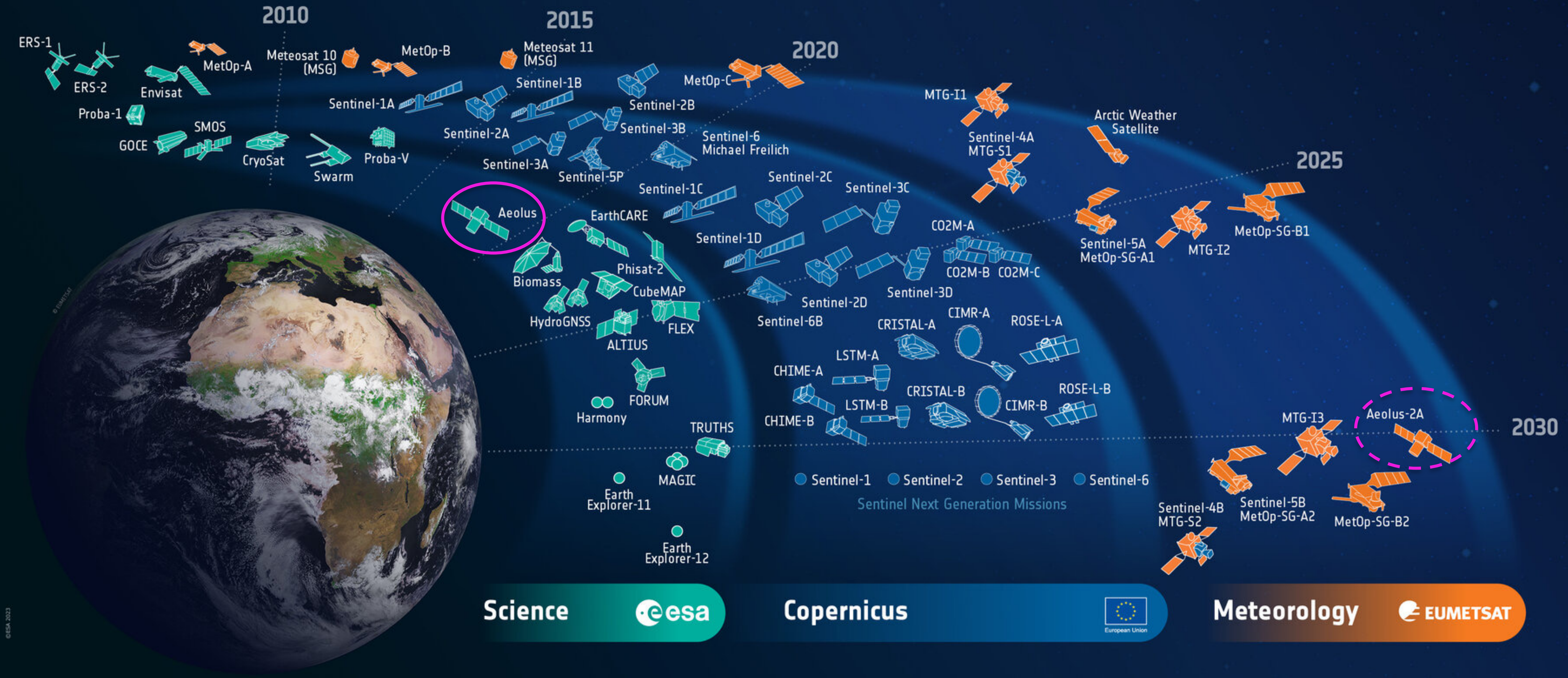
- **E**uropean **S**pace **A**gency *Earth Explorer* mission to measure profiles of wind globally
  - Chosen in 1999
  - Named from Greek mythology: “Keeper of the Winds”

- Payload: Doppler wind lidar (DWL); ALADIN: **A**tmospheric **LA**ser **D**oppler **IN**strument
- **Technology demonstration**; 3 year mission
- Satellite and instrument built by Airbus Defence and Space
- Status of mission:
  - After a decade delay, due to instrument technical problems, it was successfully launched on **22 August 2018**
  - Aeolus was the **first wind lidar in space** and first European lidar in space
  - Produced data from 3 September 2018 until 30 April 2023. Exceeded the nominal mission lifetime; currently in end-of-life phase before deorbiting.





ESA-developed Earth Observation missions



Aeolus satellite mission continued

Scientific Objectives:

1. **Improve the quality of weather forecasts** by providing **global profile measurements of horizontal line-of-sight wind** in troposphere and lower stratosphere
2. To advance understanding of atmospheric dynamics and climate processes

Long-term goal:

Demonstrate space-based Doppler wind lidar's capability for operational use

- Global Observing System **still** lacks globally distributed **wind profiles**
- NWP impact was expected be greatest in **tropics** due to **lack of conventional wind profiles** and atmospheric **dynamical arguments** on importance of wind versus mass (T, p) information near equator

Geostrophic adjustment theory

Rossby radius of deformation: $R = \frac{\sqrt{gh}}{2\Omega sin\Phi}$

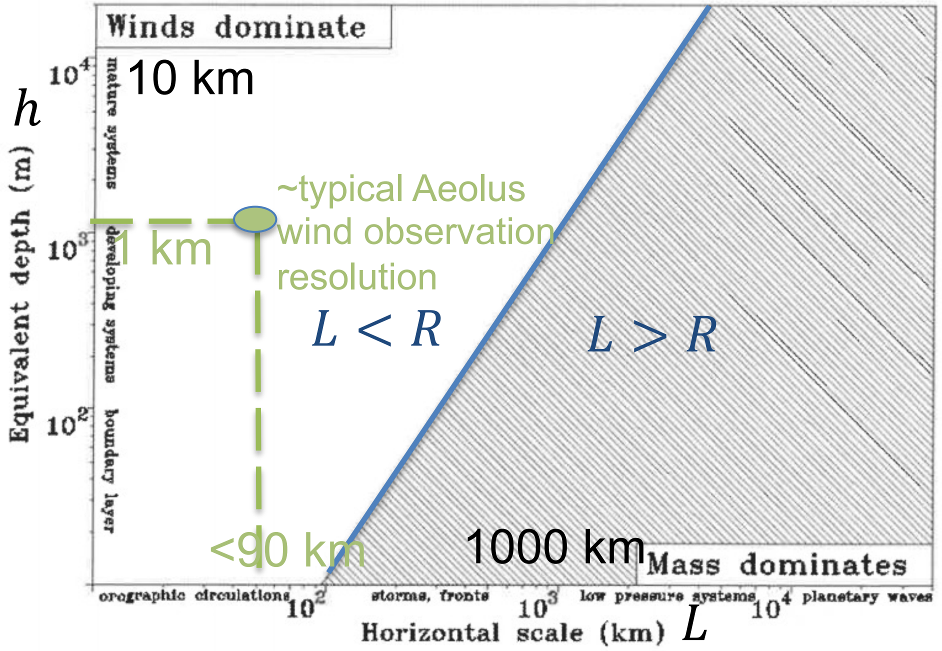
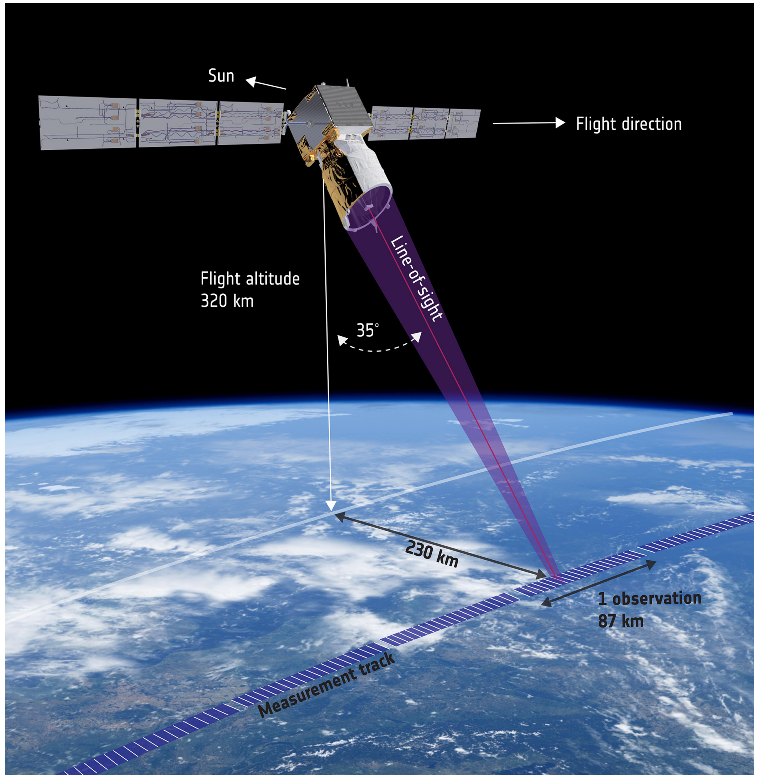


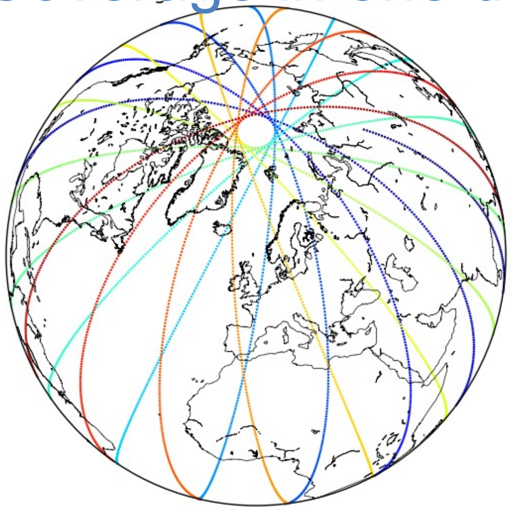
Figure 2.3. Rossby radius of deformation for a latitude of 45° as a function of horizontal scale and equivalent depth. Open area denotes the range within which the wind field dominates the atmospheric dynamics, and three-dimensional wind measurements are important.

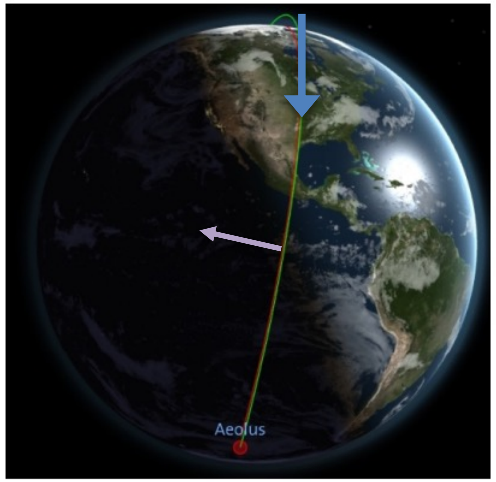
courtesy: ESA, 1999

Aeolus measurement principle



Coverage in one day

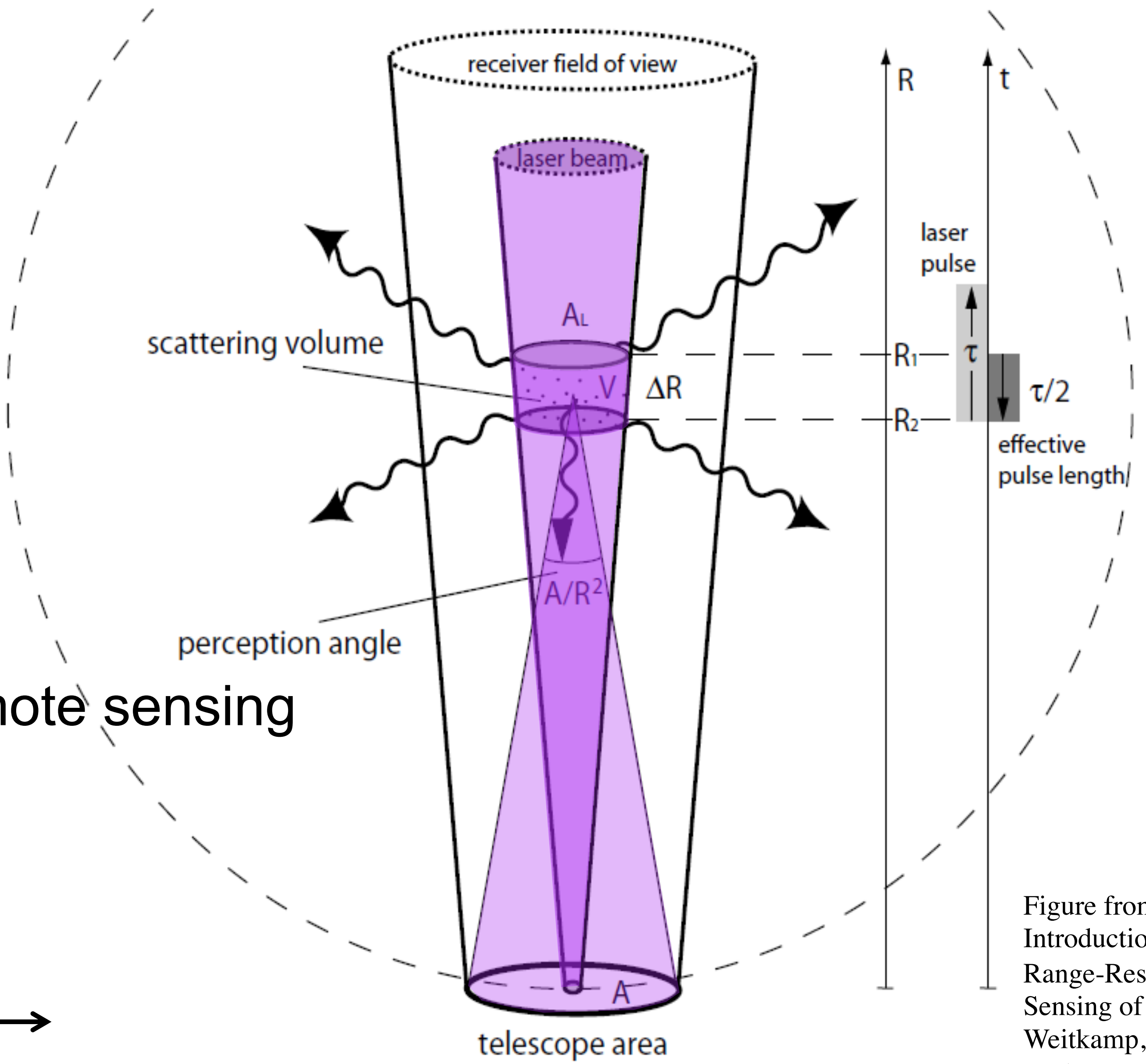




- **Satellite: sun-synchronous, dawn-dusk** (06/18 Local Solar Time) near **polar orbit**; 111 orbits per week
  - *At terminator between day and night to keep solar panels in light and to minimise reflected solar radiation (noise)*
- **Instrument:**
  - *Direct detection* **Doppler wind lidar** operating at ~355 nm (long wave ultraviolet), fires ~50 **laser** pulses per second
  - Two receiver channels:
    - **Mie** to determine winds from **cloud** and **aerosol** backscatter (“cloudy”-air)
    - **Rayleigh** to determine winds from **molecular** backscatter (clear-air)
  - Lidar line-of-sight points:
    - 35° off-nadir to determine **horizontal line-of-sight wind component** *(not vector wind)*
    - Perpendicular to satellite-earth relative velocity (yaw steering)
    - To **dark side** to minimise reflected solar radiation (noise)

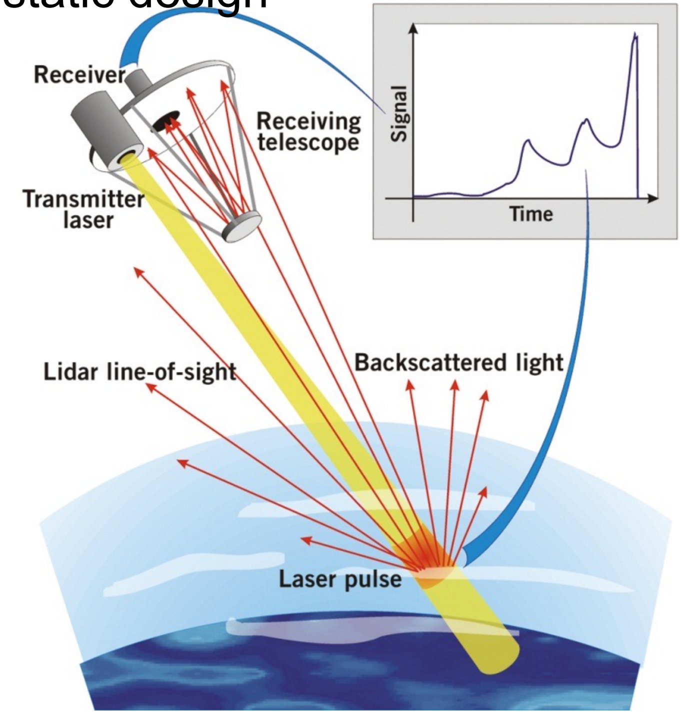
Introduction to lidar, Doppler wind lidar and Aeolus' specific design

Lidar (light detection and ranging)



Monostatic design

Bistatic design



Active optical remote sensing

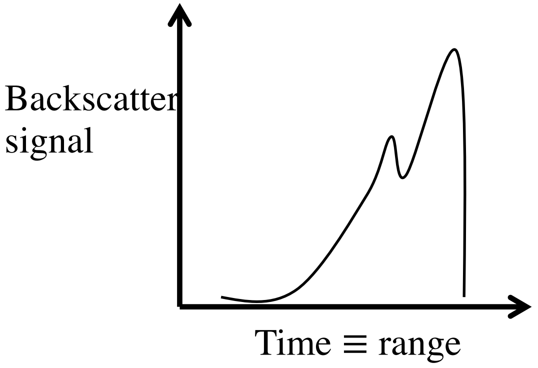


Figure from Wandinger, U. (2005), Introduction to lidar, in LIDAR—Range-Resolved Optical Remote Sensing of the Atmosphere, edited by C. Weitkamp, pp. 1–18, Springer, New York.

Lidar equation

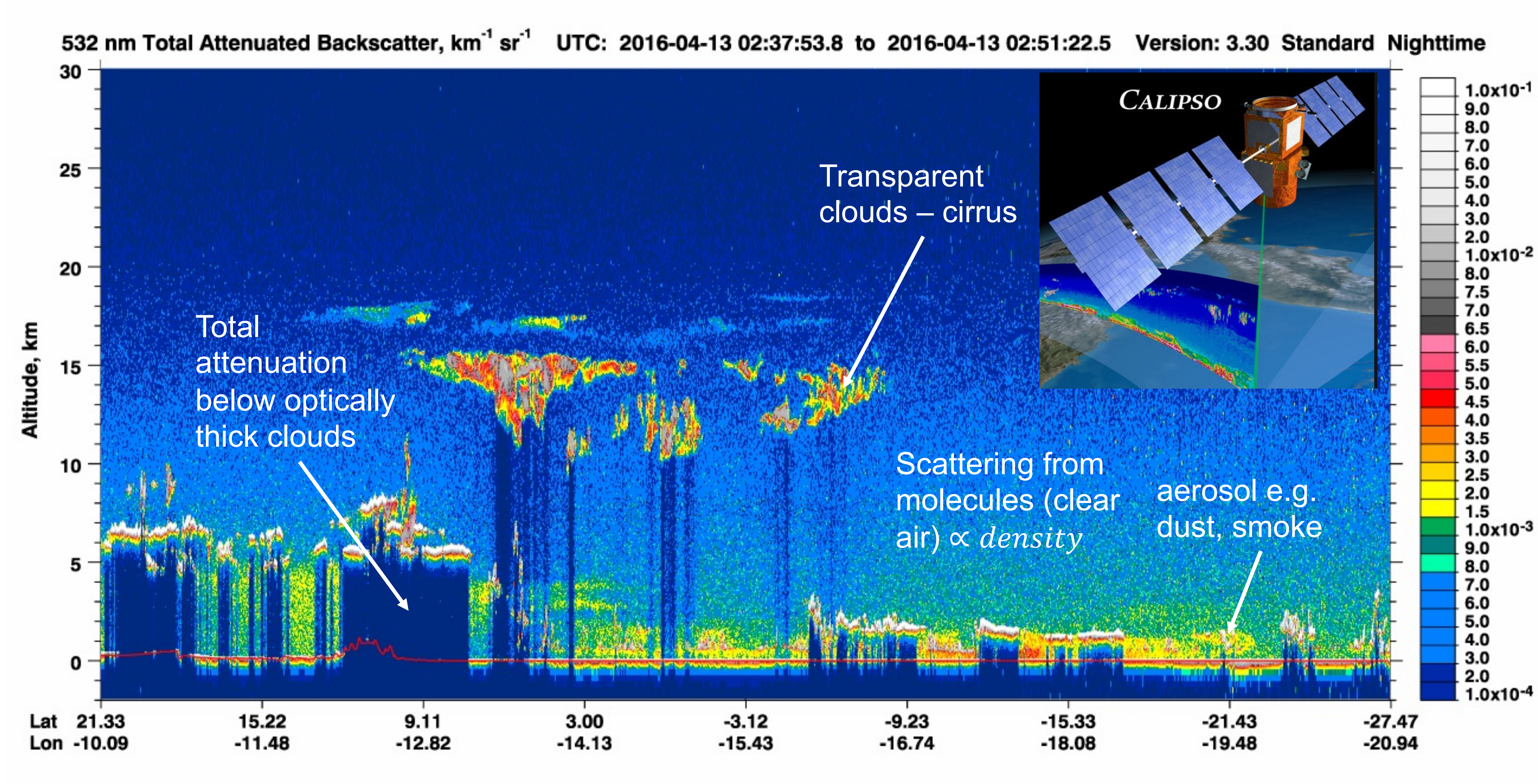
Source: Measures (1992); R.M. Measures, "Laser Remote Sensing. Fundamentals and Applications". John Wiley & Sons, 1984

- The total scattered **power received by the lidar** at a time corresponding to range *R* is:

$$P(\lambda, R) = P_L \frac{A_0}{R^2} \xi(\lambda, R) \beta(\lambda, R) T^2(\lambda, R) \frac{c\tau_L}{2}$$

- λ = laser wavelength
- R = range of scatterer from sensor
- β = volume backscattering coefficient of atmosphere
- T = one way transmission factor (Beer-Lambert law): $T(\lambda, R) = e^{-\int_0^R \alpha(\lambda, R) dR}$
- α = atmospheric attenuation coefficient
- P_L = average power in laser pulse
- A_0 = area of objective lens
- c = speed of light
- τ_L = laser pulse duration
- ξ = calibration factor (depending on spectral transmission of receiver and overlap factor)

“Lidar curtain” of space-borne lidar (CALIPSO (532 nm)), attenuated backscatter: βT^2

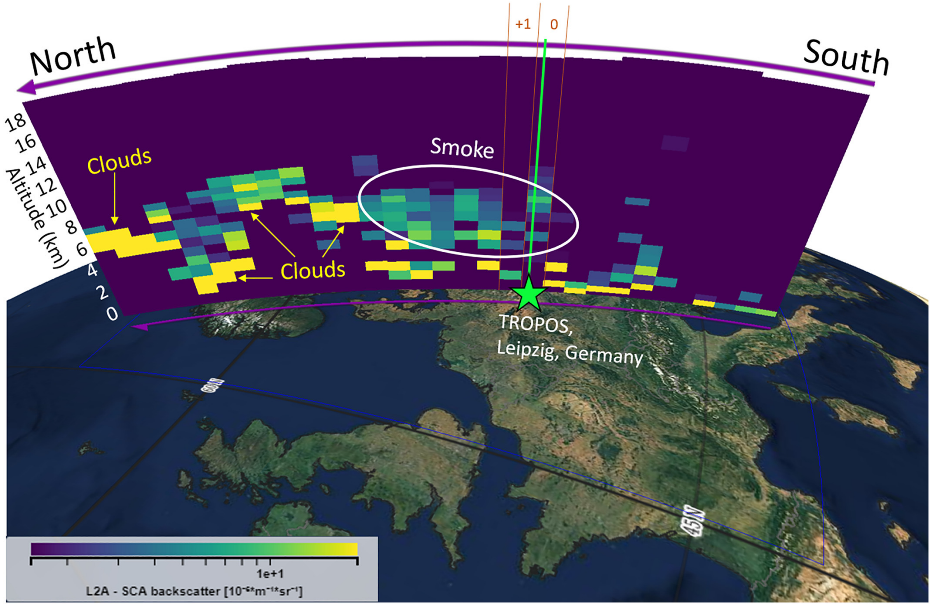


credit: NASA

What's different about a *Doppler* lidar?

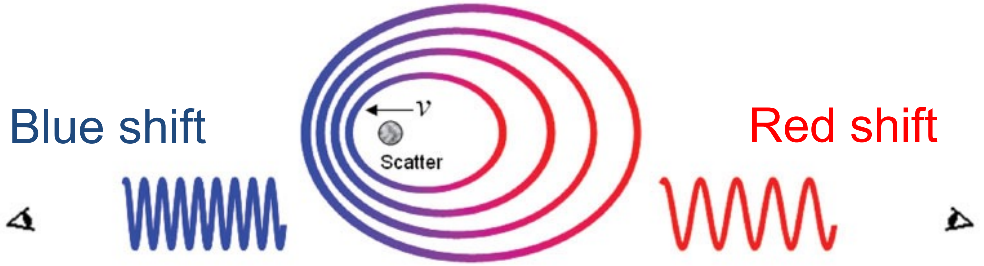
- Lidars for atmospheric composition measurements use **amplitude of backscatter signal** and **polarisation** (at several frequencies) to provide information about the **atmospheric composition**
- **Doppler lidars** measure the **change in the frequency** (Doppler shift) of the received relative to emitted light **to determine line-of-sight wind**
  - Atmospheric composition information (Level-2A product) is also provided and is a useful demonstration of space-based high-spectral resolution UV lidar for this purpose; in anticipation of ESA's EarthCARE ATLID lidar

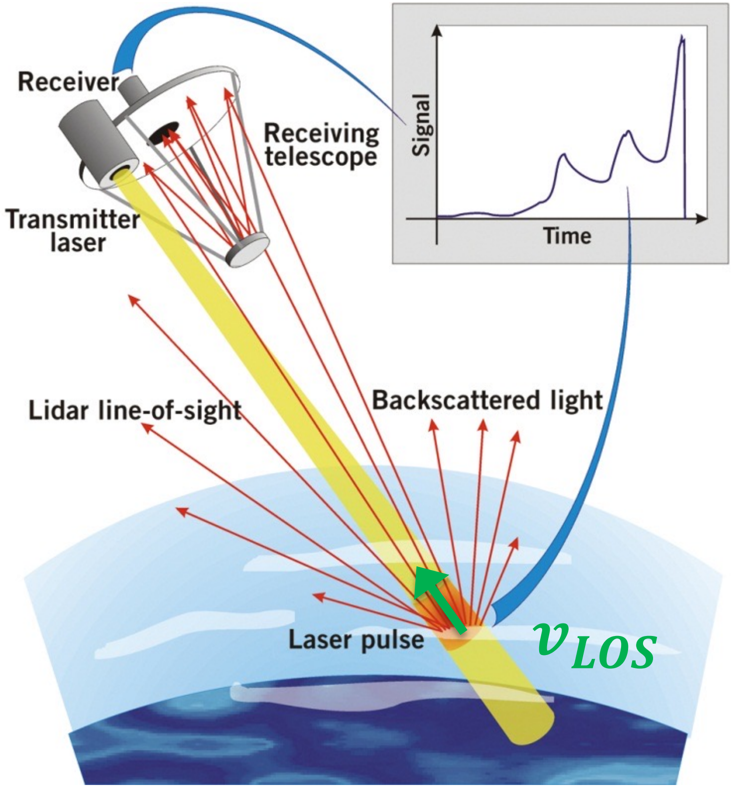
e.g. Aeolus L2A optical properties
https://doi.org/10.1029/2020GL092194



Doppler wind lidar

A DWL measures the Doppler frequency shift of backscattered light





- Doppler frequency shift: $\Delta f = 2 f_0 v_{LOS}/c$
  - Δf = change in frequency
  - f_0 = emitted frequency e.g. ~845 THz for Aeolus laser
  - c = speed of light
  - v_{LOS} = component of the atmosphere's wind velocity along the line-of-sight direction. Average speed of molecules/particles in volume of air.
- Relative Doppler shift is very small, $\frac{\Delta f}{f_0} \approx 10^{-8}$ for 1 m/s LOS wind change; need **very sensitive instrument**
- Backscattering from:
  - Air molecules (clear air), particles (aerosol/cloud) and **Earth's surface (zero wind reference)**

Aeolus operates lidar at 355 nm wavelength

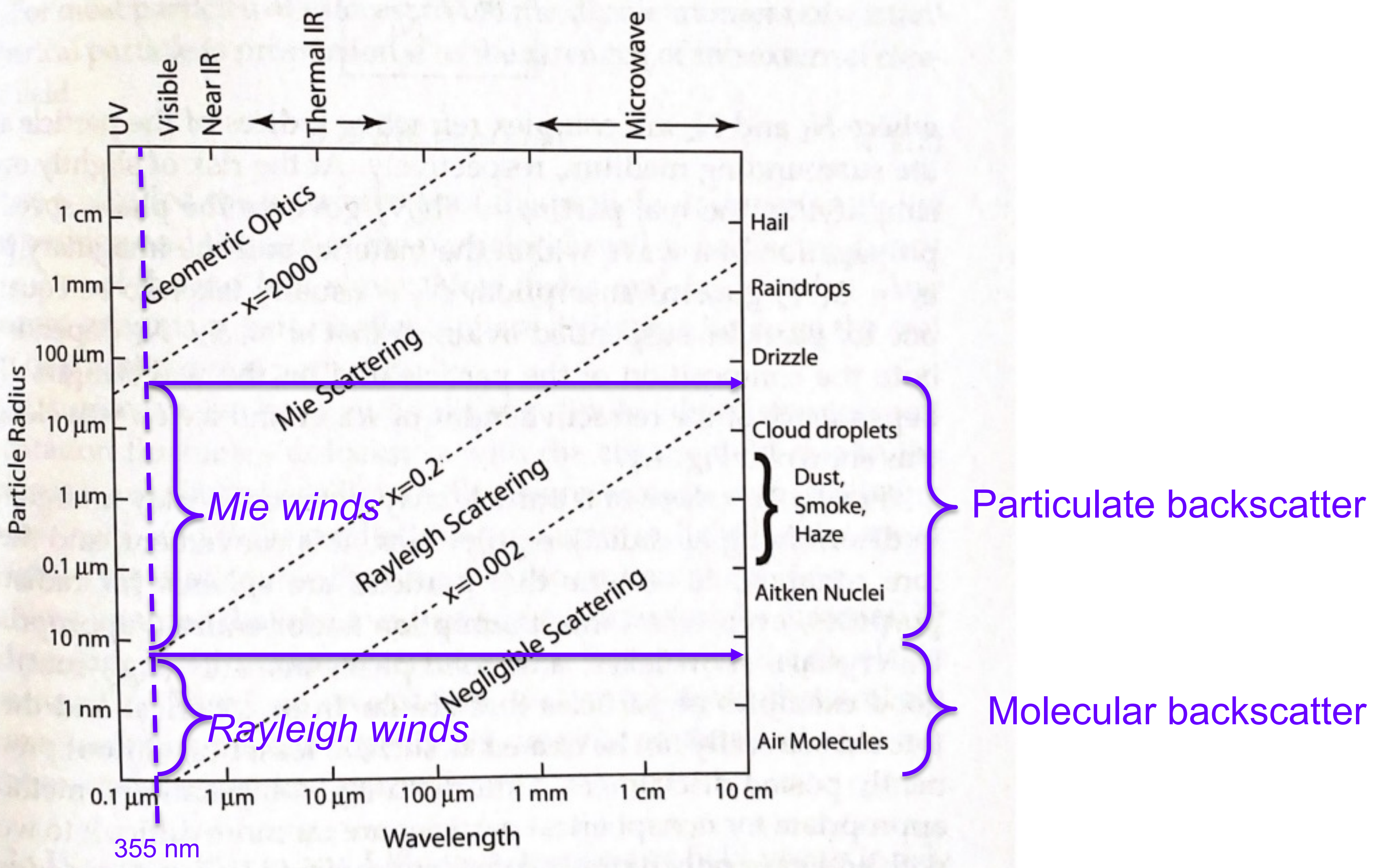
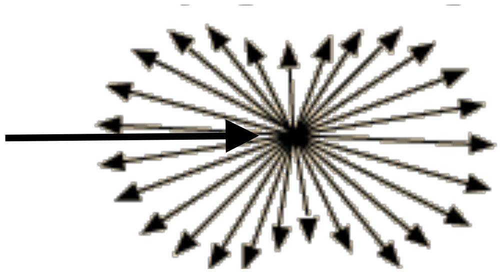
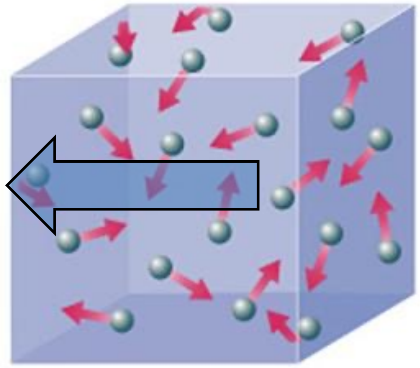


Fig. 12.1: Relationship between particle size, radiation wavelength and scattering behavior for atmospheric particles. Diagonal dashed lines represent rough boundaries between scattering regimes.

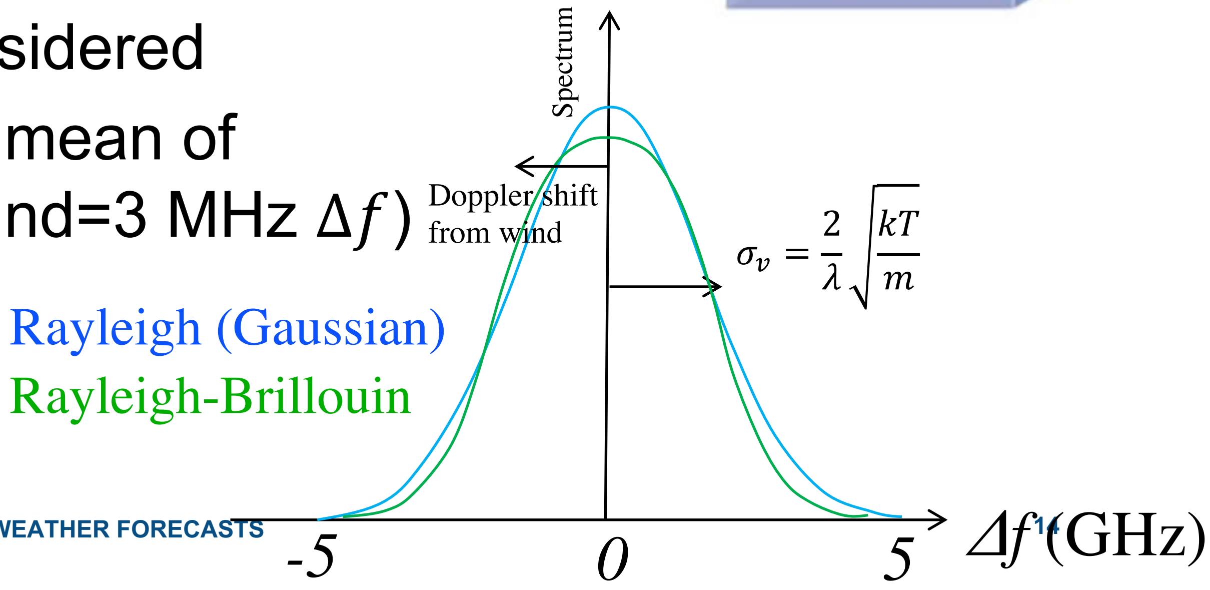
Figure from: A First Course in Atmospheric Radiation, G Petty

Winds from **clear sky** conditions; Rayleigh scattering



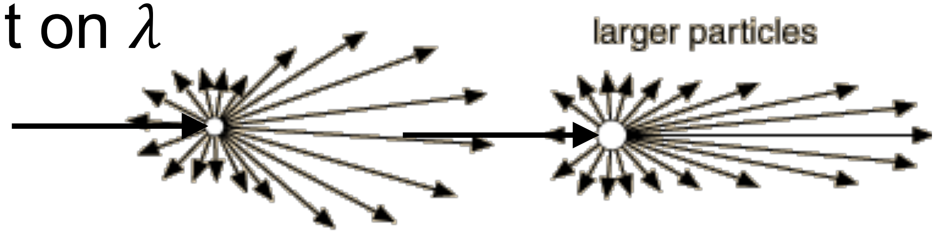


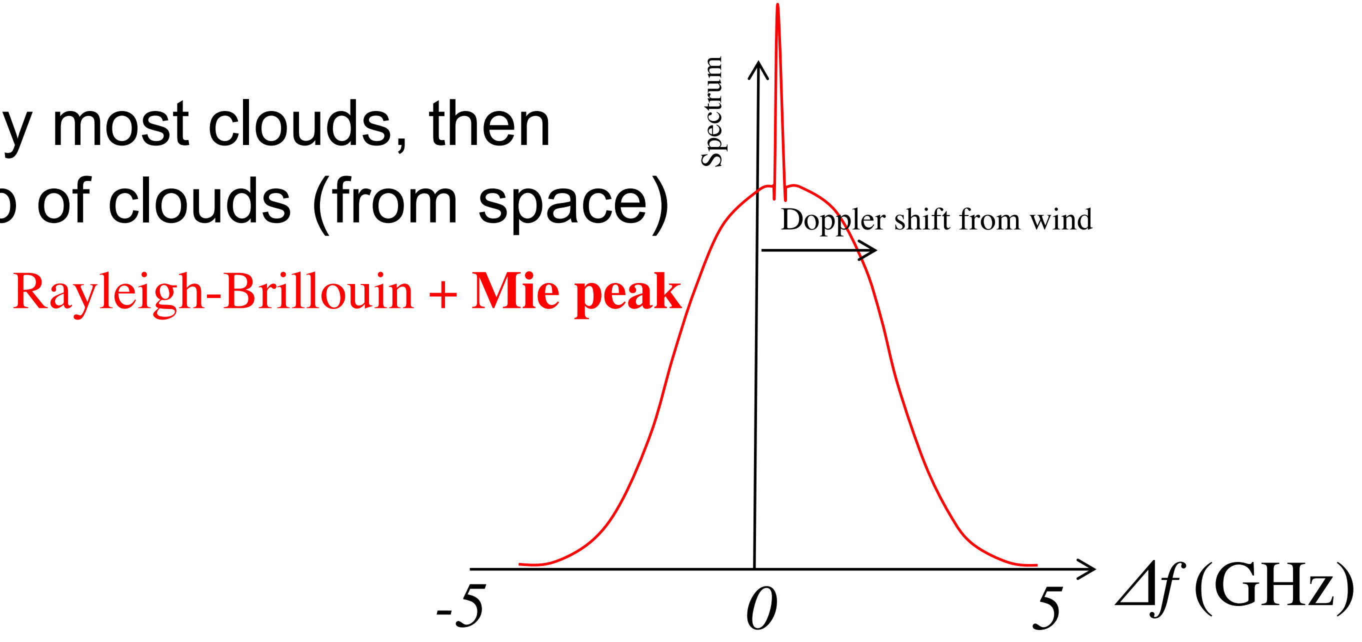
- For Rayleigh scattering: $I \propto \lambda^{-4}$; scatterer size < $\frac{\lambda}{10}$
  - For strong scattering from air molecules need short wavelength, *hence Aeolus uses* ***UV laser***
- **Thermal motion** of molecules leads to **Doppler broadening**
  - e.g. T=15 °C get σ_v=459 m/s!
  - Brillouin scattering effect due to acoustic waves (at higher pressure) has to be considered
- <u>Wind</u> measured as frequency shift in mean of broadened spectrum (1 m/s HLOS wind=3 MHz Δf)



Winds from "**cloudy**" conditions i.e. scattering from cloud water/ice droplets and aerosols; Mie scattering

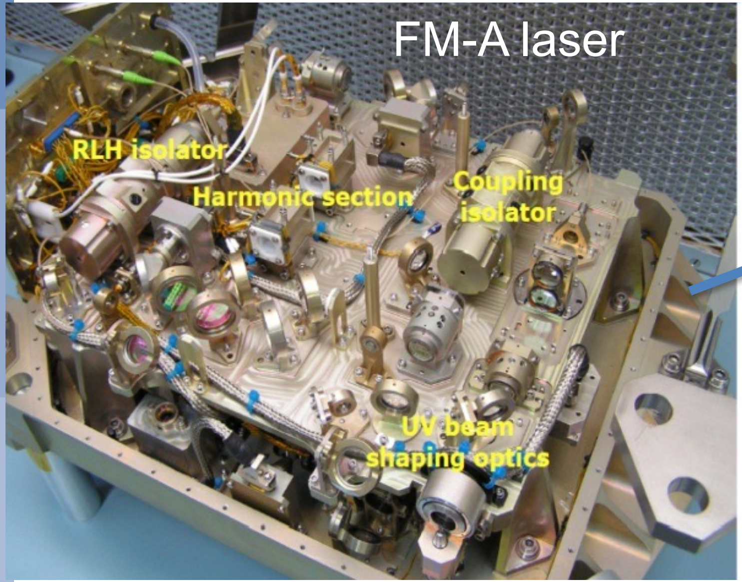
- Particle sizes ≥ λ; intensity not strongly dependent on λ
- Doppler broadening negligible (particles "heavy")
  - Narrow spectrum
  - *No temperature, pressure dependence*
- Wind measured as frequency shift in mean of the narrow Mie spectrum
- Since light is strongly attenuated by most clouds, then measure winds mostly from the top of clouds (from space)



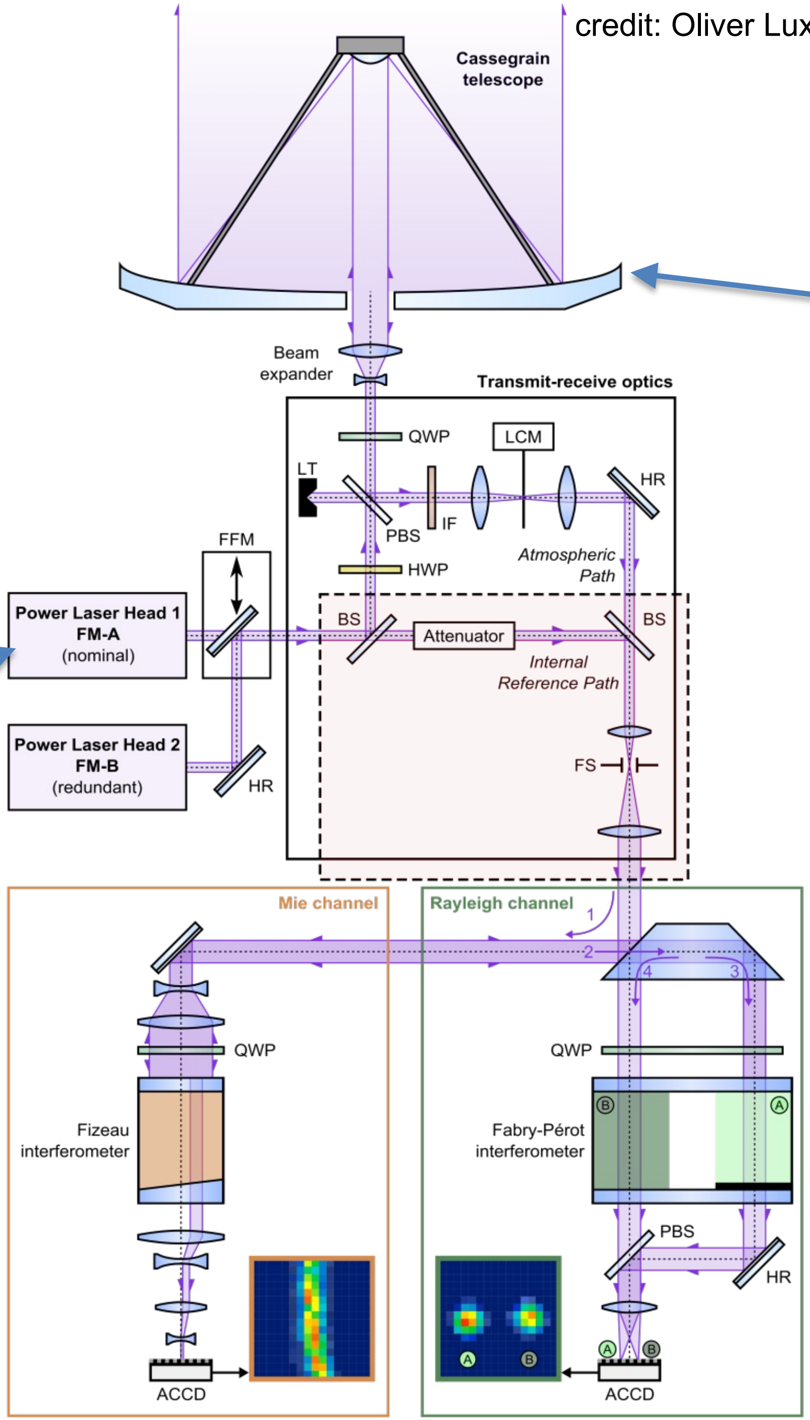


Aeolus's payload: ALADIN: Atmospheric LAser Doppler Instrument

credit: ESA/Airbus



Complicated optical instrument!



credit: Oliver Lux (DLR)

credit: ESA/Airbus

Rayleigh channel method

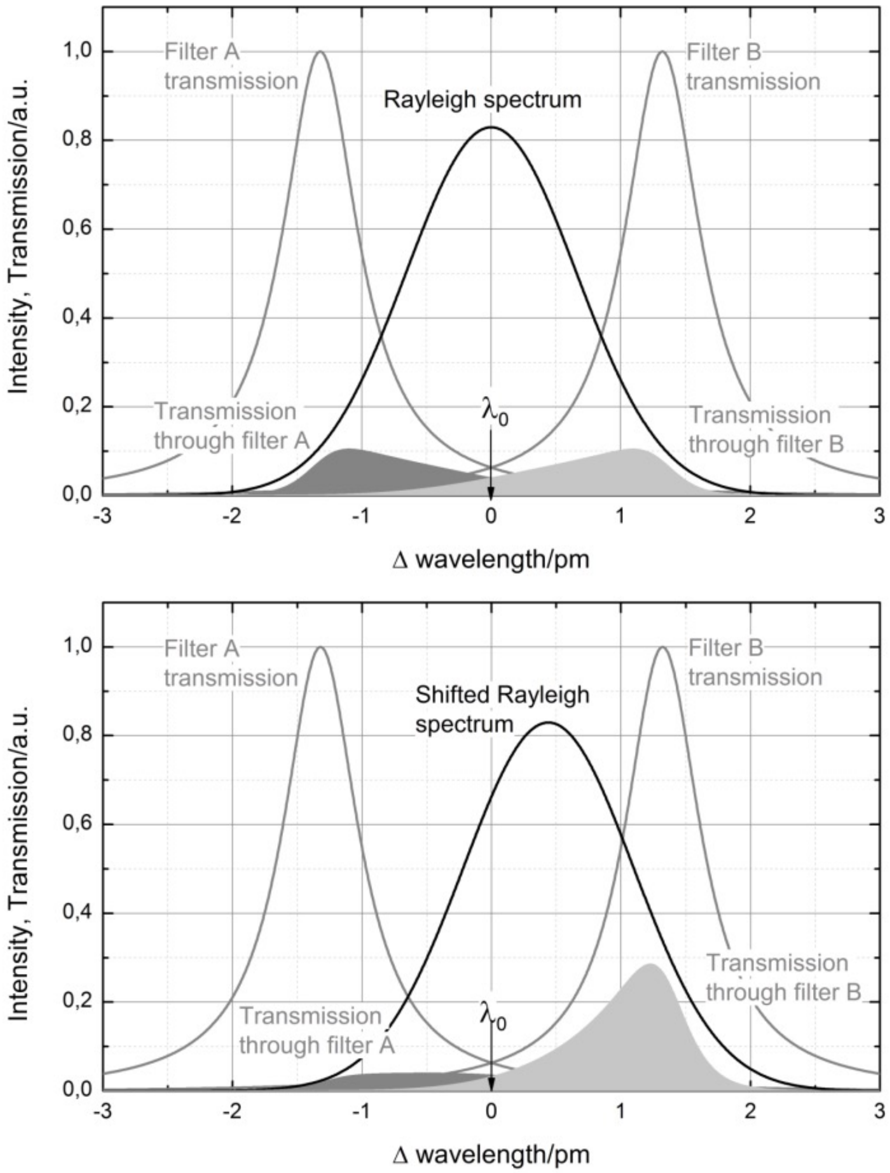


Figure from Reitebuch (2012): Wind Lidar for Atmospheric Research, in Springer Series

Doube-edge Fabry-Pérot interferometer

- transmission maximum occurs for a specific wavelength of light; which differs for each interferometer

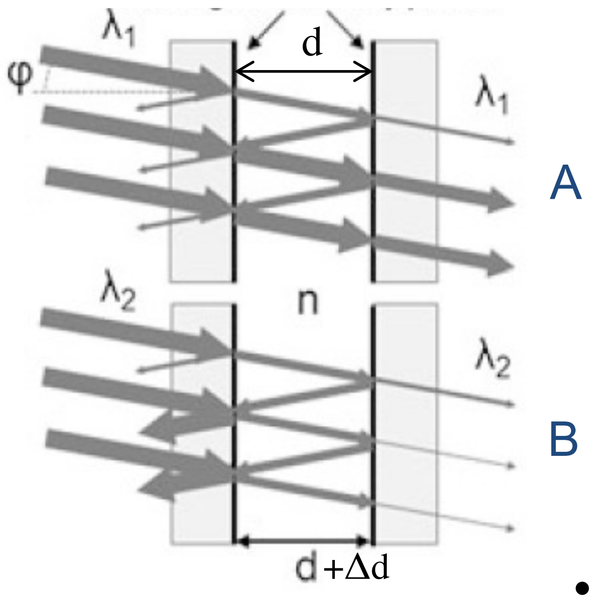
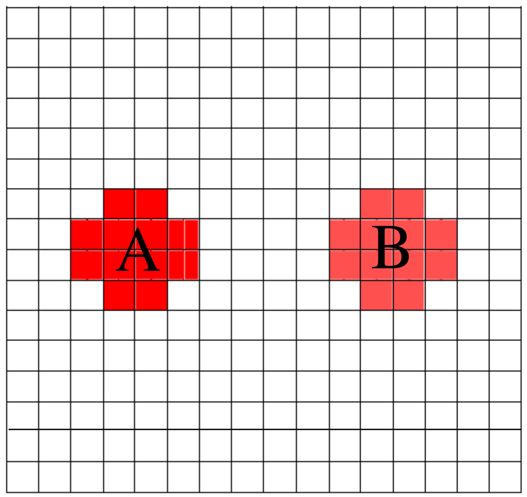


Figure from Reitebuch (2012) The Spaceborne Wind Lidar Mission ADM-Aeolus, Springer

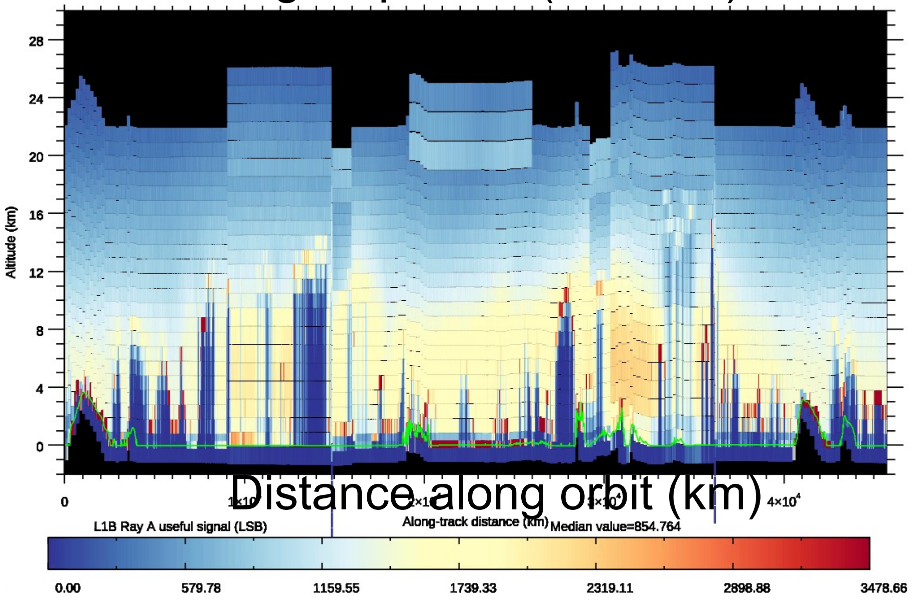


- Rayleigh spots imaged on accumulation CCD
- Contrast of spots $R = \frac{A-B}{A+B}$ calibrated against frequency

Real Rayleigh channel signals (L1B data) over an orbit

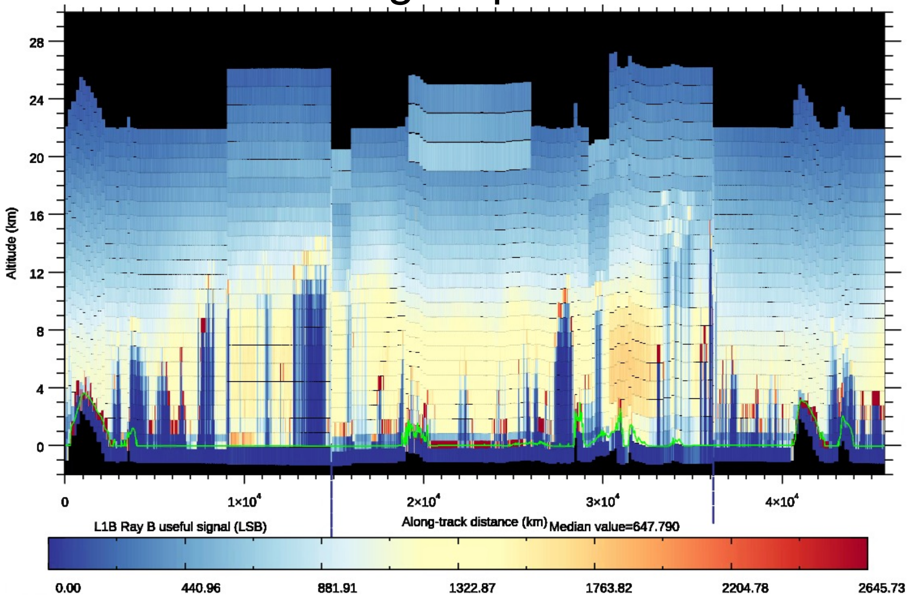
Channel A signal photon (*electron*) counts

Altitude (km)



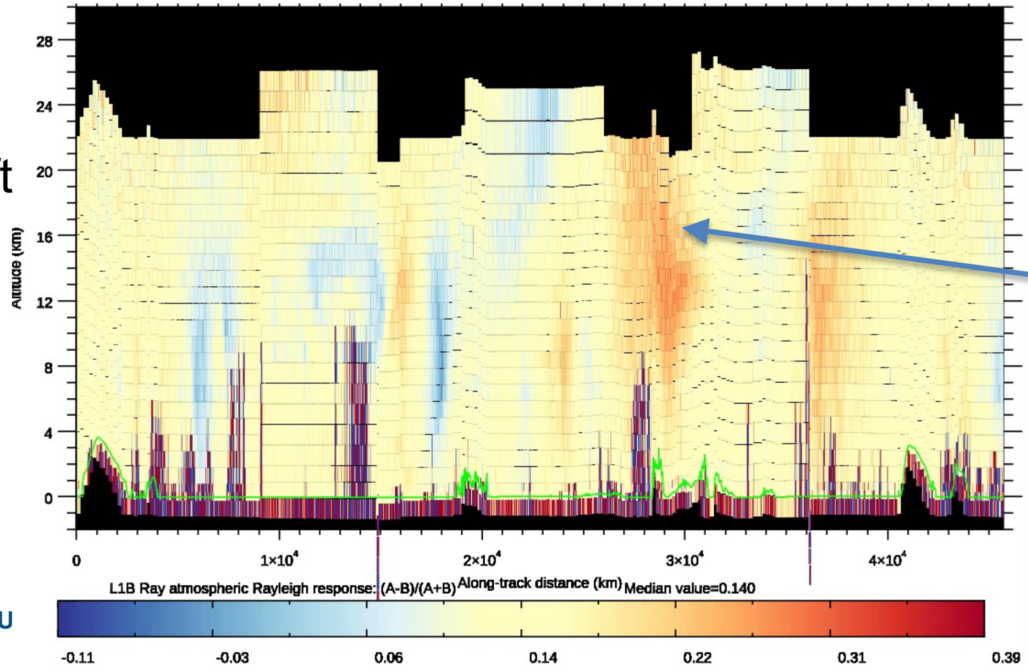
Distance along orbit (km)

Channel B signal photon counts



Rayleigh response ∝ Doppler shift

$$R = \frac{A-B}{A+B}$$



Can see variations in Rayleigh response due to horizontal wind

EU

Mie channel method

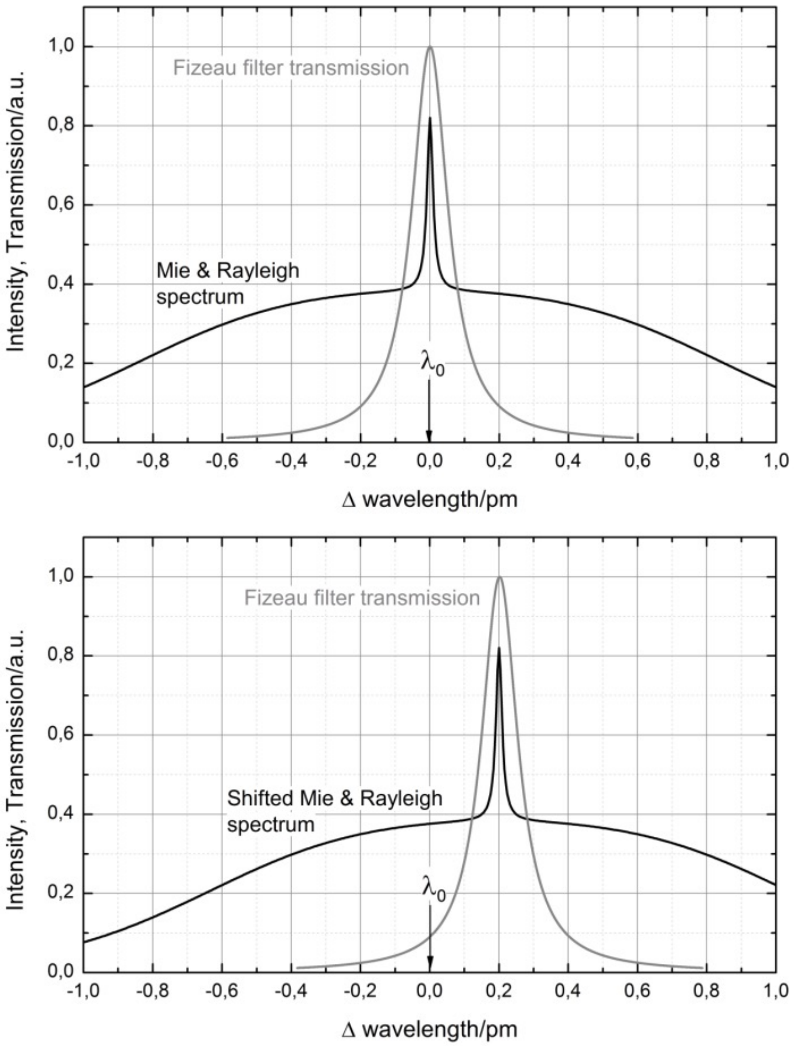
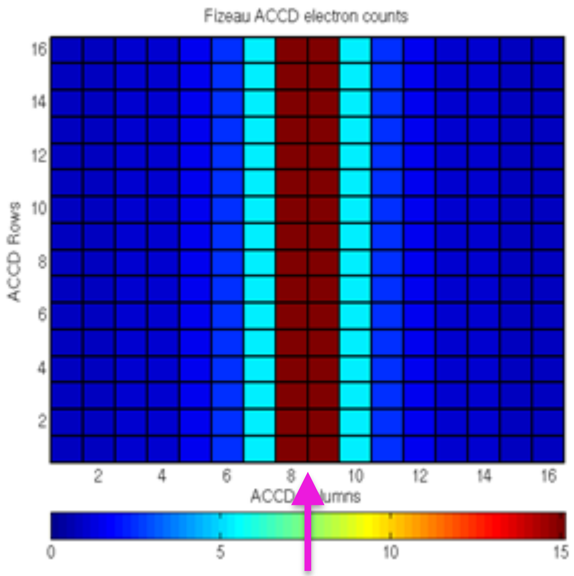
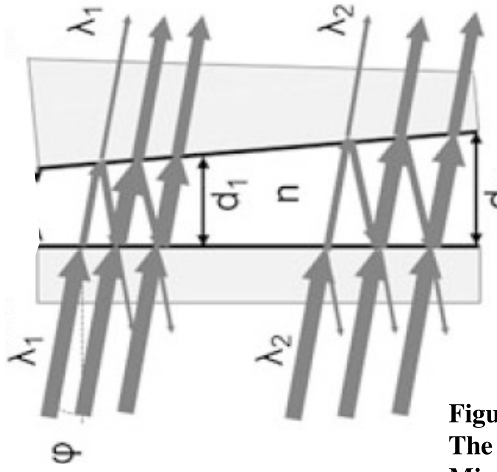


Figure from Reitebuch (2012): Wind Lidar for Atmospheric Research, in Springer Series

Mie fringe on ACCD





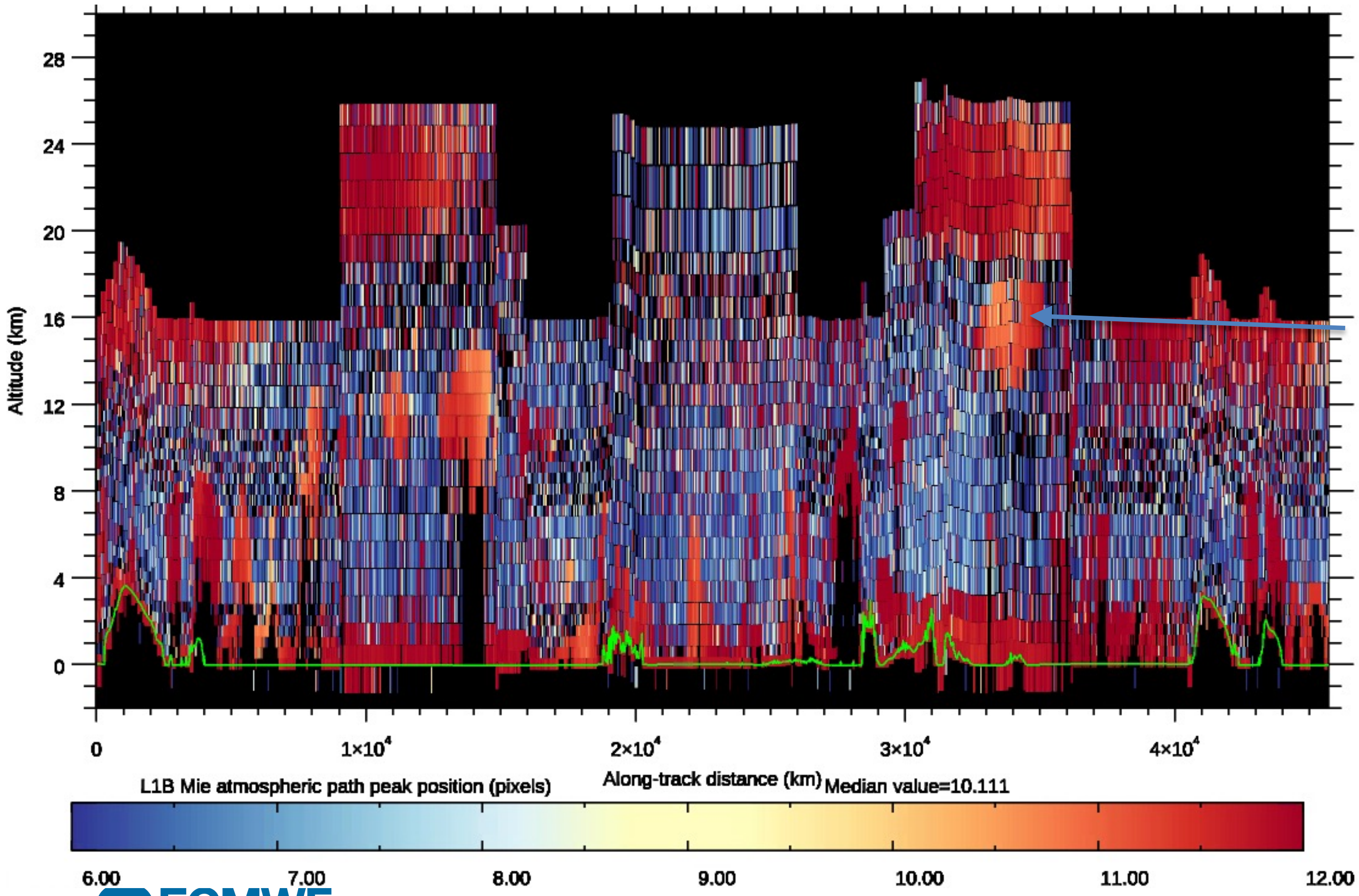
Fringe position ∝ f, calibration required

- Narrowband **Fizeau interferometer**
- Transmission max. for f depends on x-position – thickness of gap (*wedge* shape)

Figure from Reitebuch (2012) The Spaceborne Wind Lidar Mission ADM-Aeolus, Springer

Real Mie channel signals (L1B data) over an orbit

Mie fringe peak position ∝ Doppler shift



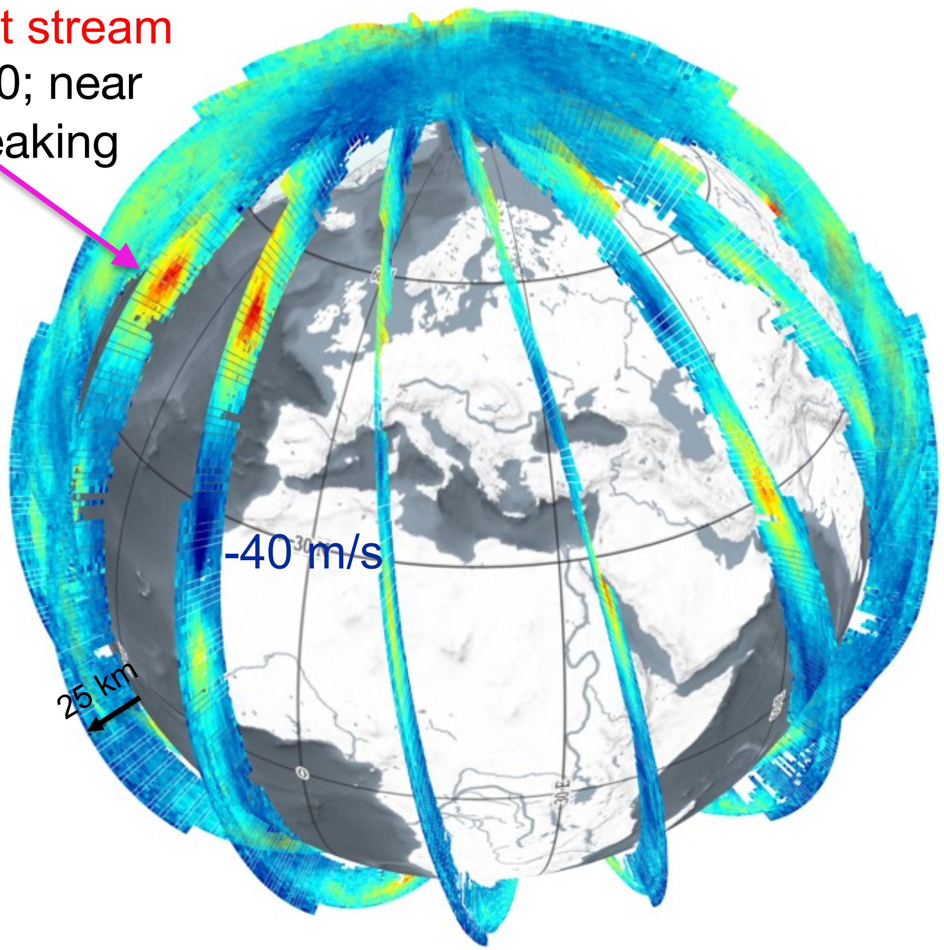
Can see variations in Mie fringe position due to horizontal wind

Some features of DWL

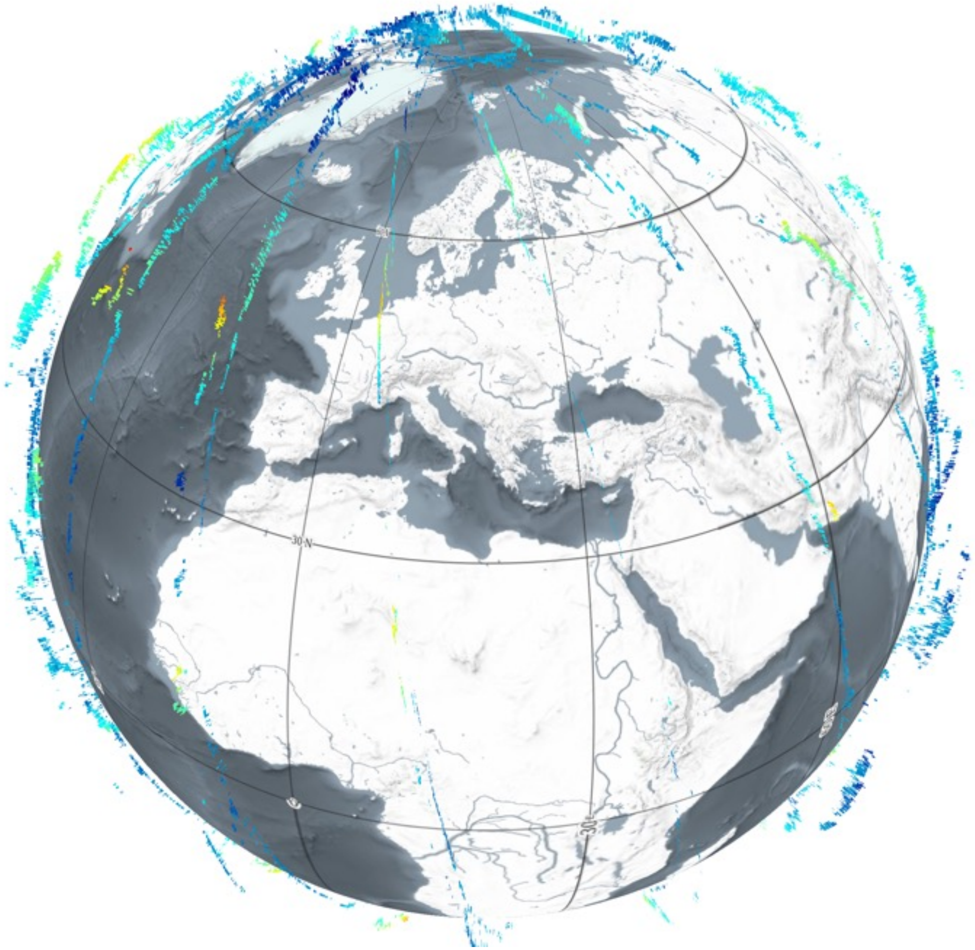
- Advantages:
  - Provides Doppler shift (hence LOS wind speed) profiles
  - Good vertical and horizontal (along-track) resolution is possible
    - Complementary to relatively poor vertical resolution of passive radiances
  - Not many processing steps and assumptions to get wind i.e. *reasonably direct measure of the geophysical variable*
- Disadvantages:
  - Totally attenuated by optically thick cloud or aerosol, need *radar* to see within clouds
  - Space-borne DWL:
    - Complex technology – still quite new
    - Several LOS "looks" are required to get vector wind, nominally have wind component along the LOS
    - Limited sampling across-track i.e. "poor swath" (e.g. sub-satellite "curtain")
    - Due to $1/R^2$ dependence of signal, then needs to be relatively *low altitude orbit* (closer to target)
  - Calibration can be tricky

Examples of Aeolus Level-2B horizontal line-of-sight (HLOS) winds

120 m/s jet stream
9 Feb 2020; near record-breaking



12-hours of L2B **Rayleigh-clear** HLOS winds



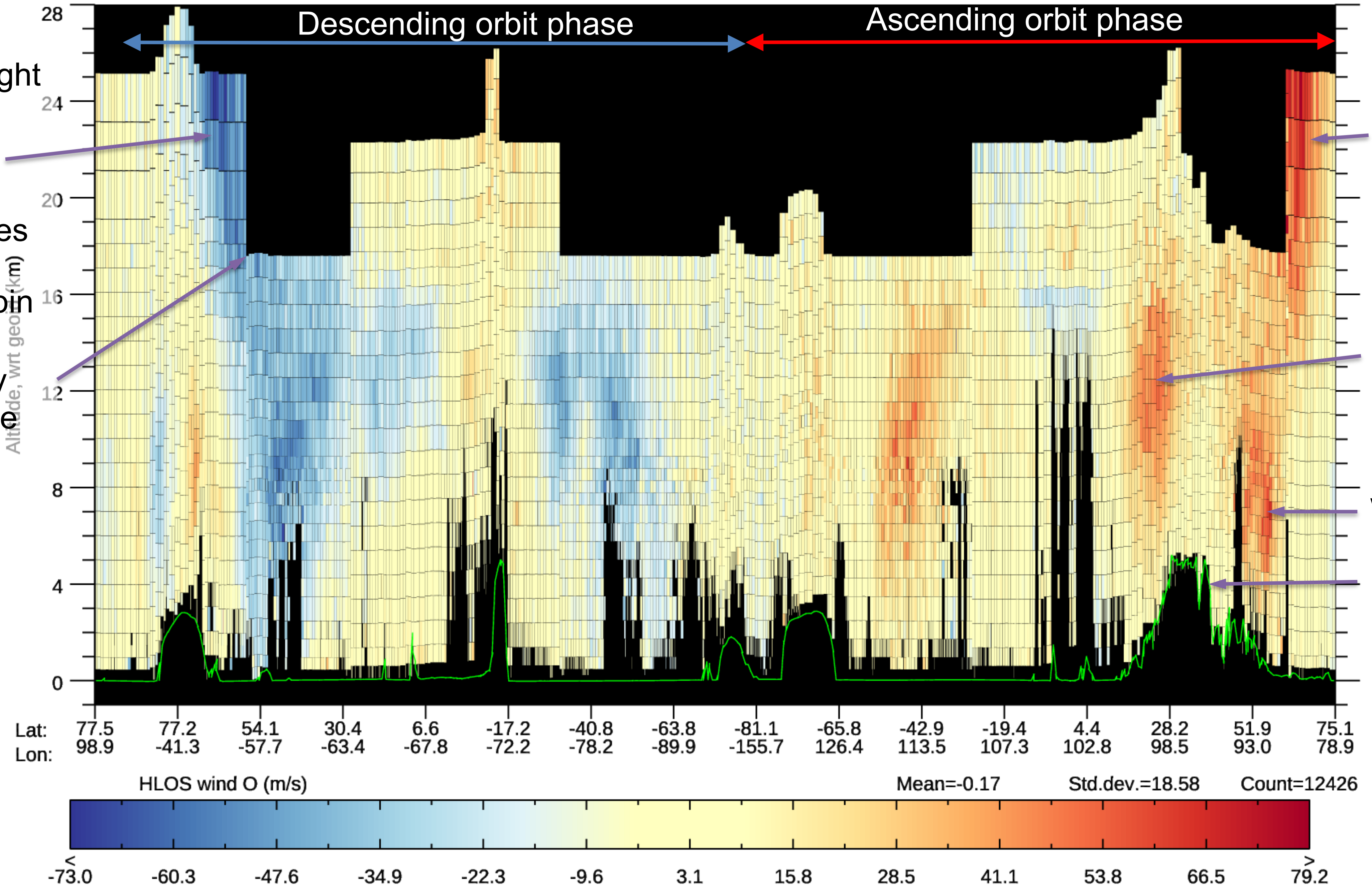
12-hours of L2B **Mie-cloudy** HLOS winds

10 Feb 2020

Aeolus L2B Rayleigh-clear **and** Mie-cloudy HLOS winds (**1 orbit**)

Polar-night jet (aka Polar Vortex); westerlies

Range-bin settings can vary along the orbit



Polar-night jet; westerlies)

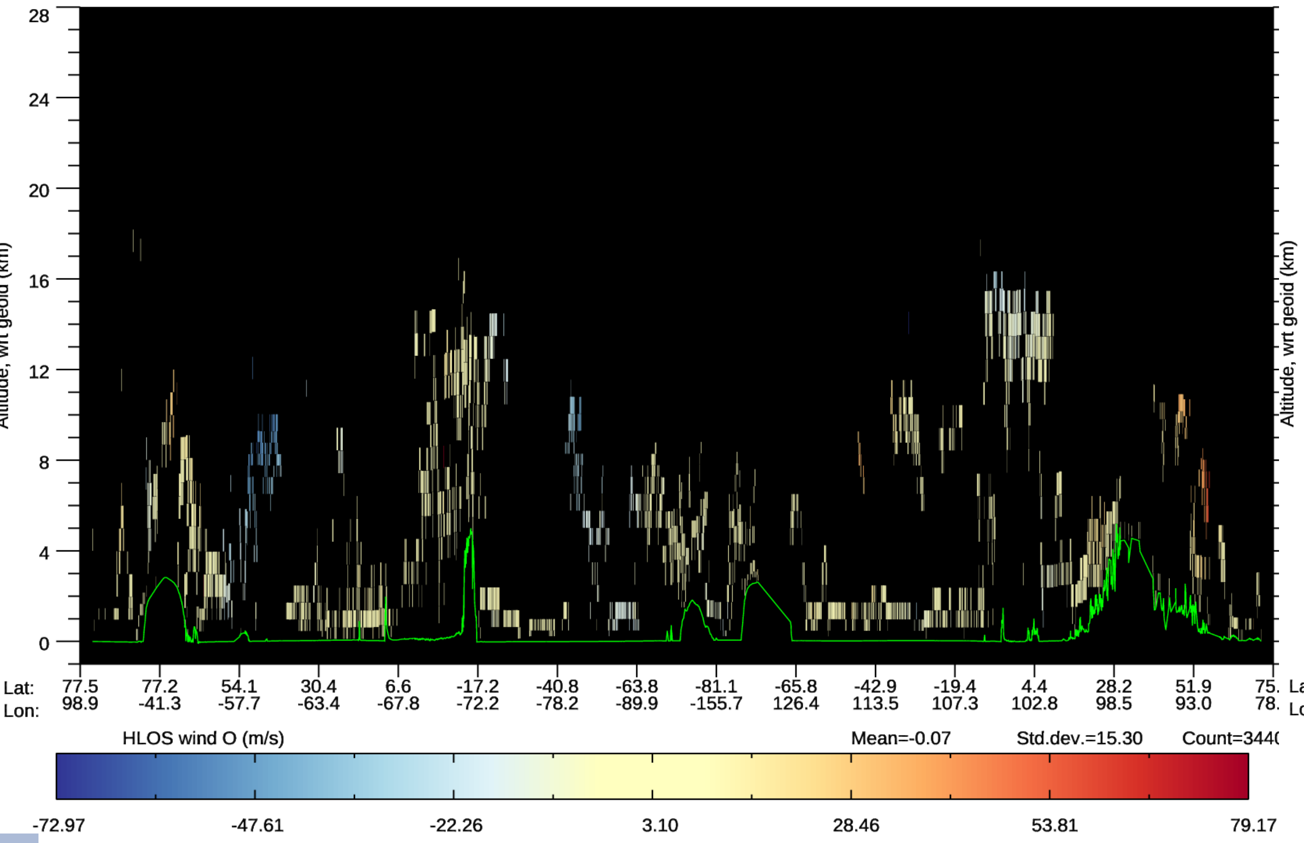
Subtropical jet; westerlies

Polar front jet; westerlies

Mountains

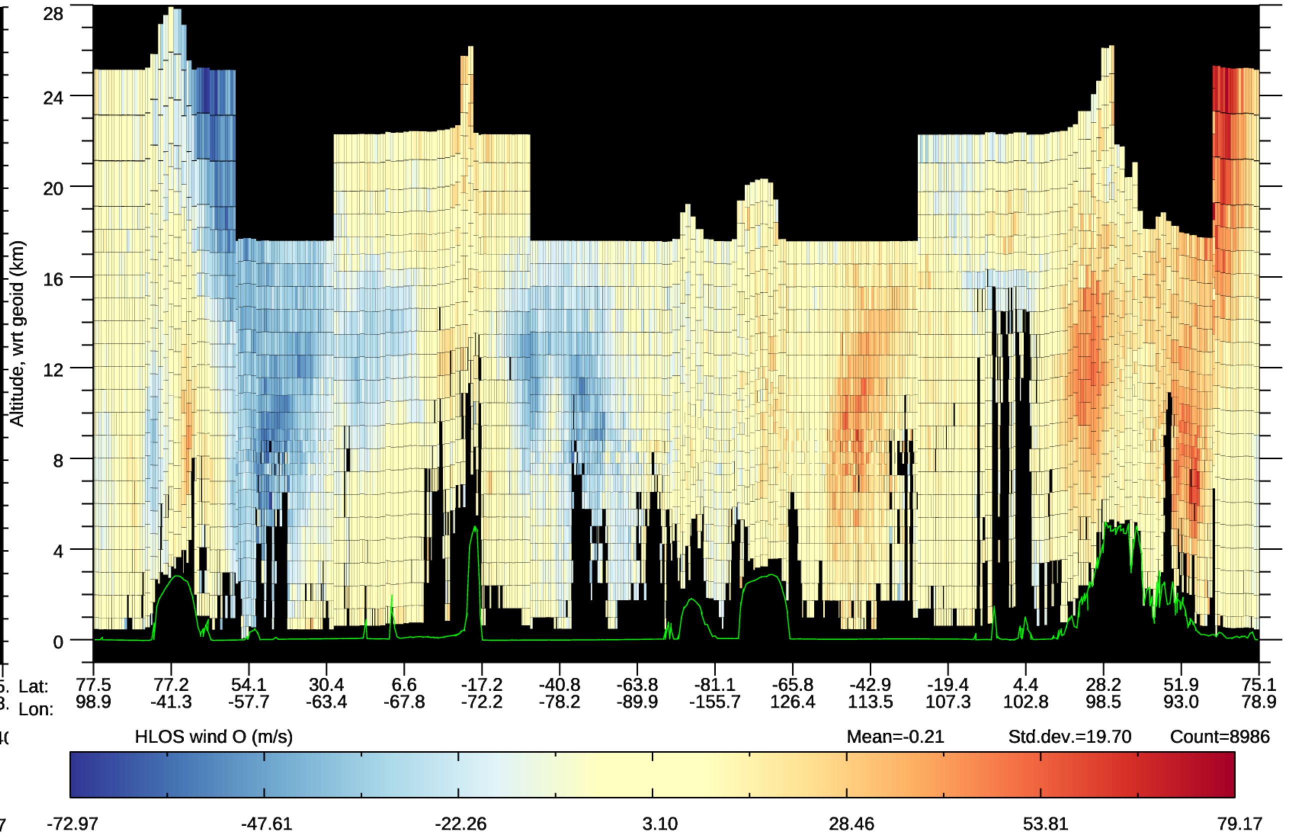
Rayleigh and Mie winds are complementary

Mie-cloudy L2B HLOS winds



~14 km horizontal averages

Rayleigh-clear L2B HLOS winds



~86 km horizontal averages

ECMWF

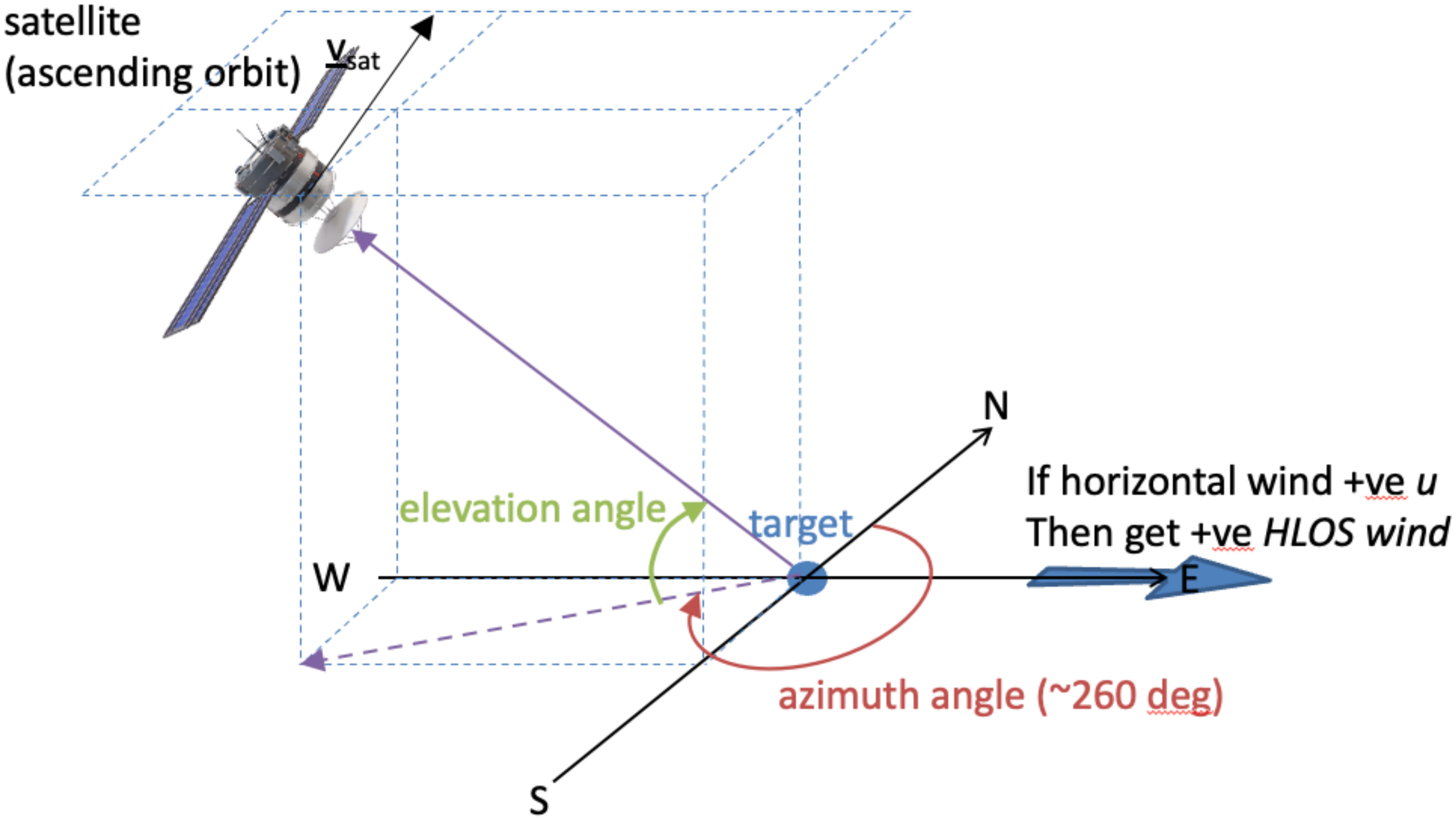
Use of Aeolus in NWP at ECMWF

L2B HLOS (horizontal line-of-sight) wind assimilation

- ECMWF forward model: HLOS forward model
  - Interpolation of model wind to obs geolocation **point**
  - Calculate HLOS wind from model wind vector (*u*,*v*)

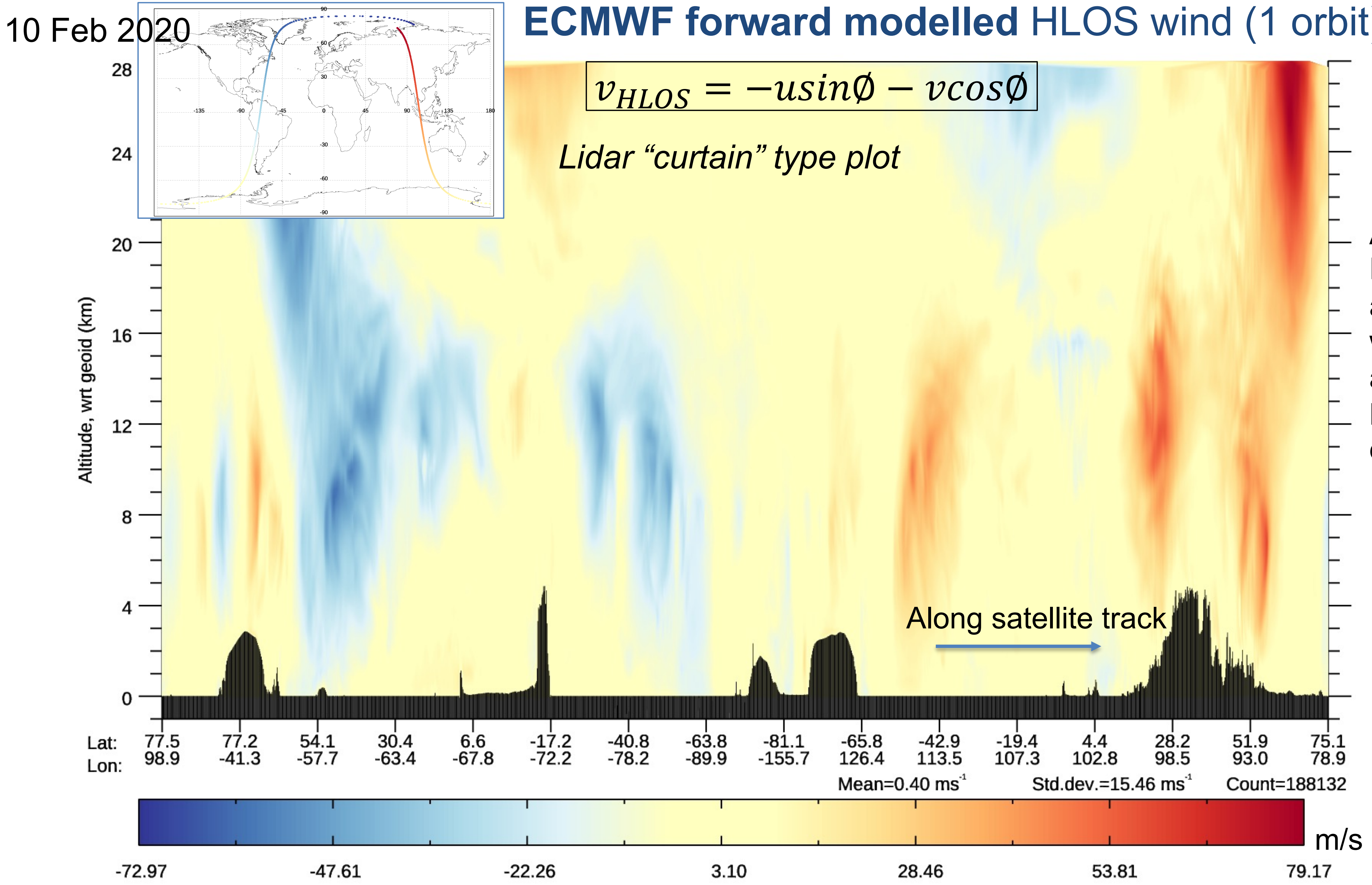
$$v_{HLOS} = \underline{v}.\underline{\hat{d}} = -u\sin\emptyset - v\cos\emptyset$$

∅=azimuth angle of line-of-sight



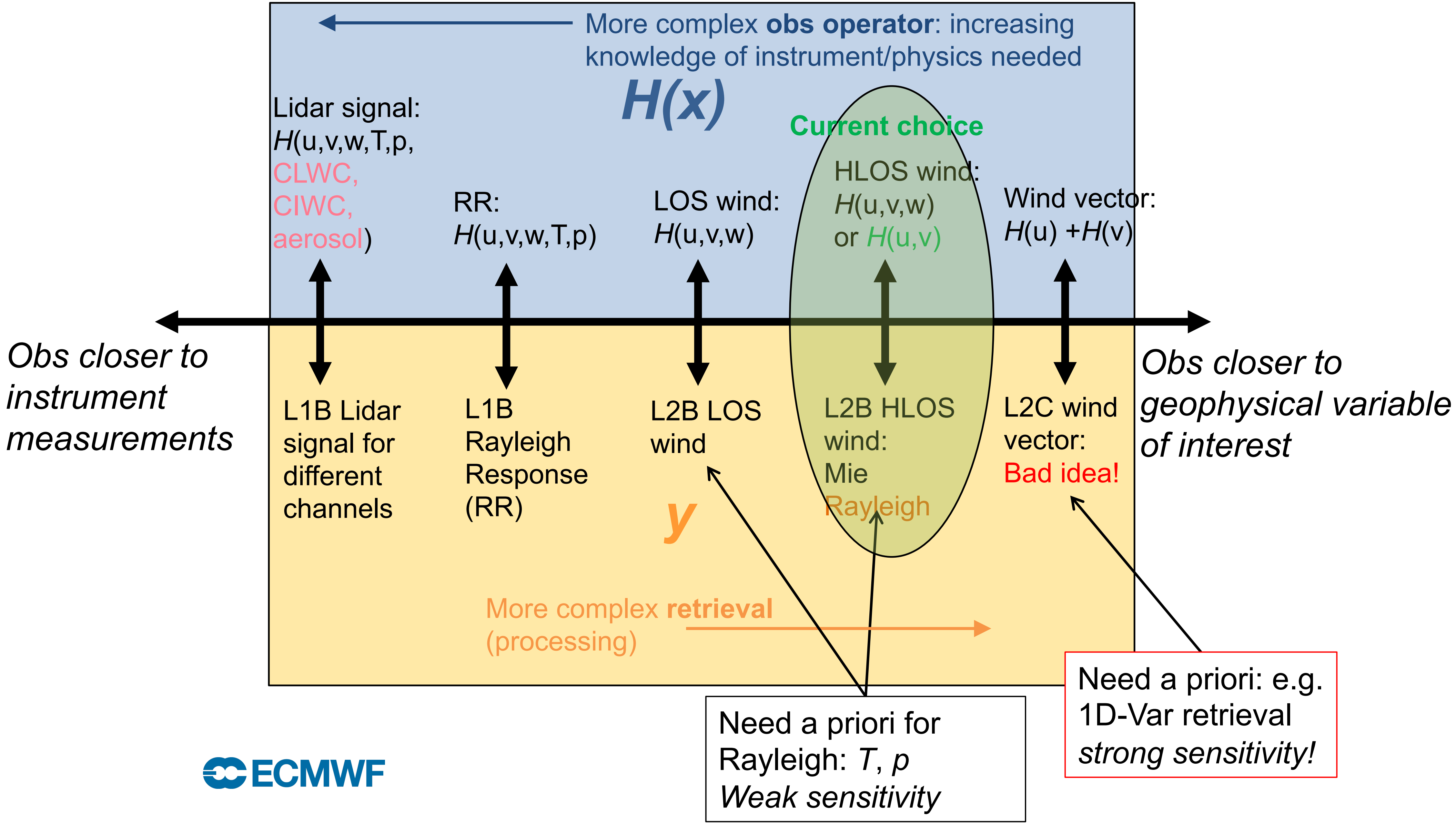
- **Assigned observation error (R matrix)** uses L2B processor estimated instrument noise and representativeness error for Mie-cloudy

ECMWF forward modelled HLOS wind (1 orbit)



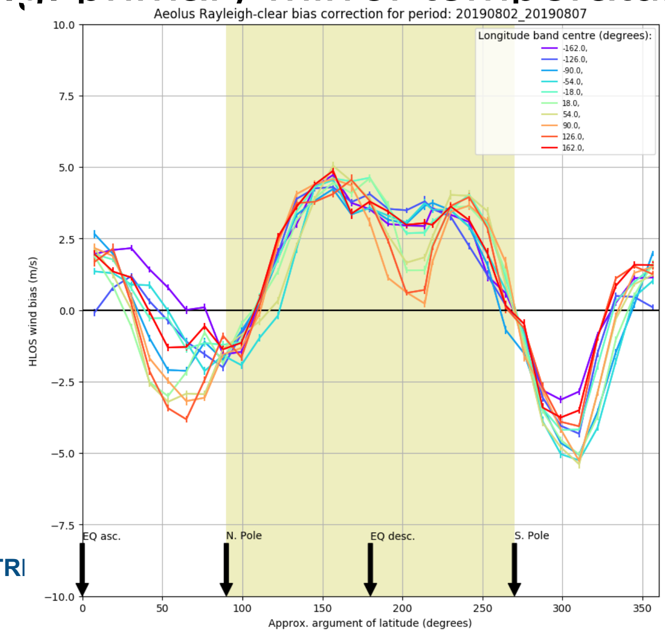
Aeolus HLOS winds are positive if wind blowing away from LOS pointing direction

What to assimilate from Aeolus for NWP?

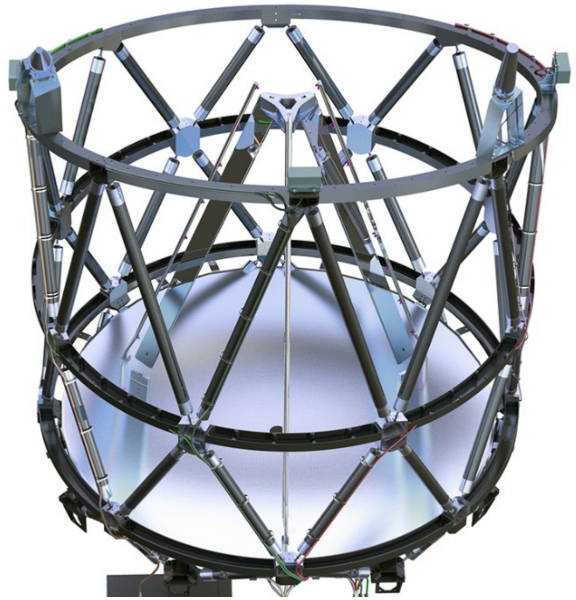


Aeolus L2B wind usage in global NWP

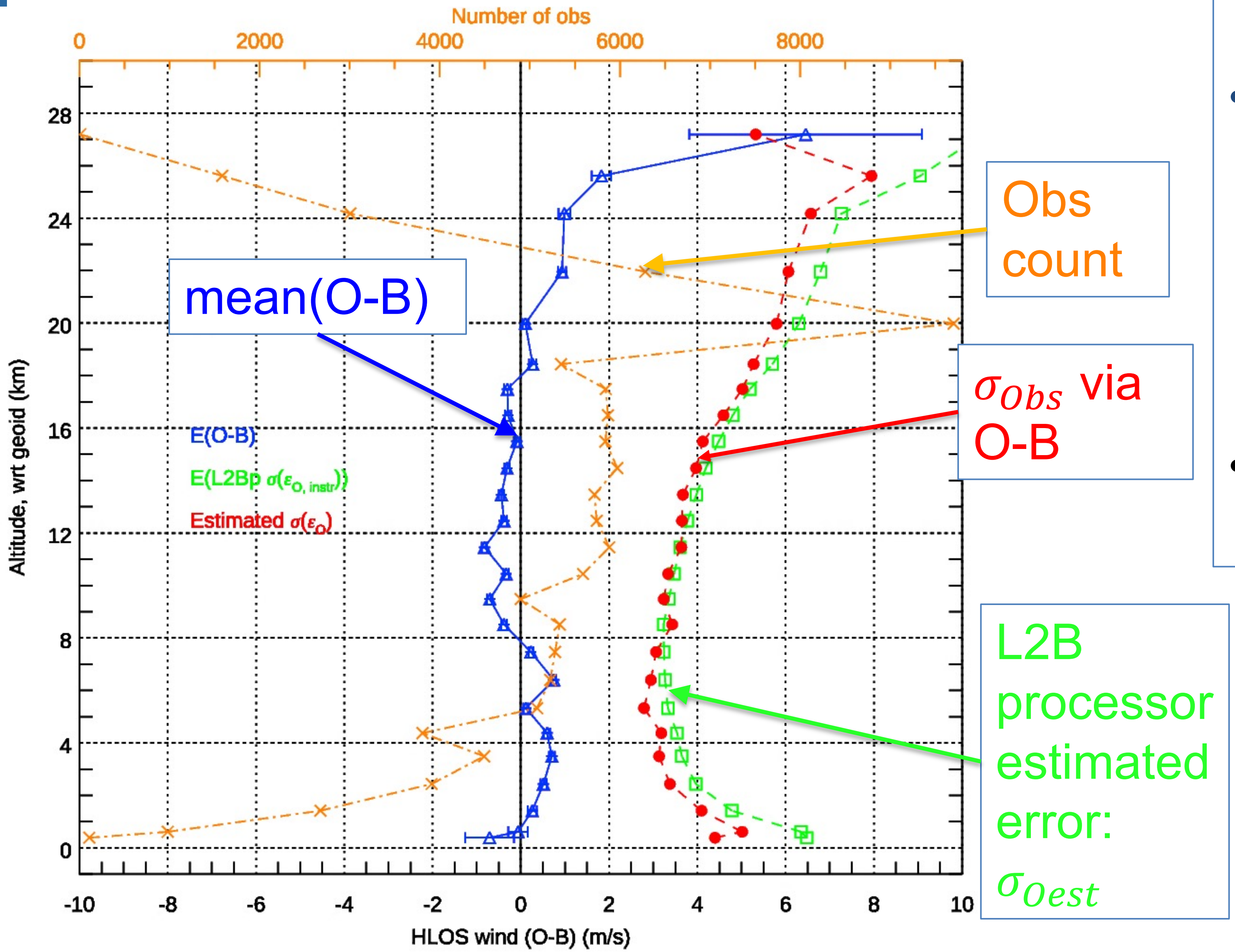
- Positive NWP impact demonstrated
  - Operationally assimilated at ECMWF **from 9 January 2020 to 30 April 2023**
- Many NWP centres showed positive impact; operationally assimilated at DWD, Météo-France, Met Office and NCMRWF
- Being a relatively new technique, still finding ways to improve ground processing algorithms (L1B, L2B, calibration processors) and its usage:
  - **Data quality was not as good as hoped for** i.e. significantly noisier winds, larger biases than expected
  - Lower signal levels -> larger noise
  - Unexpected sources of bias e.g. primary mirror temperature-gradient sensitivity (0.3K range of gradient across mirror!)



M1 mirror
Ø 1.5 m

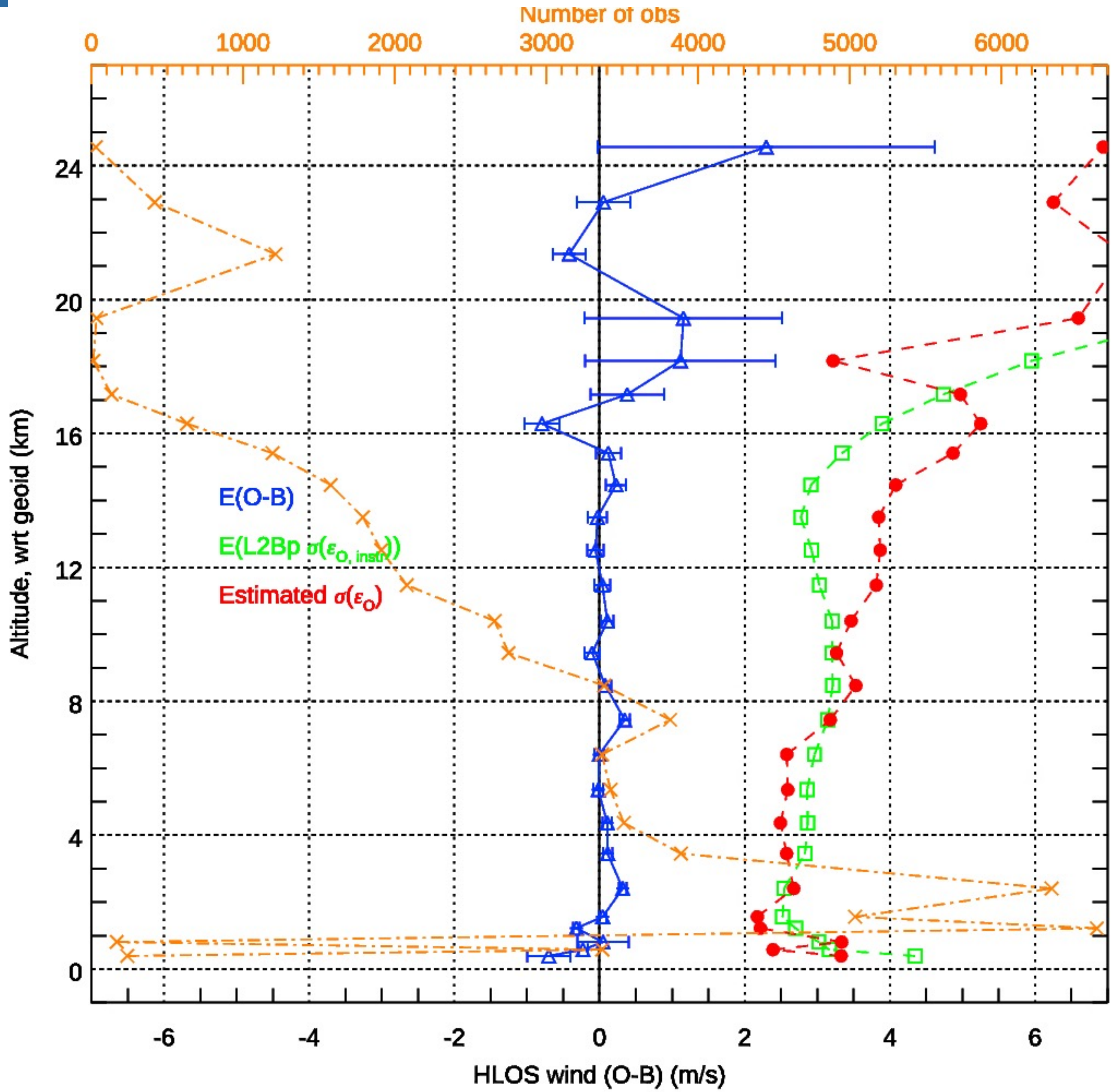


Global HLOS wind **O-B** departure statistics for L2B **Rayleigh-clear**, **31 Jan 2023 (a good period)!**



- Global average bias is reasonable
- *Estimated* observation error from O-B departures $\sqrt{st.dev.(O-B)^2 - \sigma_B{}^2}$
  - Profile average **= 4 m/s**
  - Still larger than we hoped for before launch
- Compare: radiosonde u-wind assigned obs. error is ~2 m/s

Global HLOS **O-B** statistics for **L2B Mie-cloudy**, **31 January 2023**



- Global average bias is reasonable and stable with time
- *Estimated* observation random error from O-B departures $\sqrt{st.dev(O-B))^2 - \sigma_B{}^2}$ is
  - Profile average = **2.8 m/s**
- Mie averaging length scale is ~17 km (Rayleigh is ≤ ~86 km)
- *Mie noise better despite finer horizontal resolution than Rayleigh*

Aeolus signal levels during mission – signal dropped at steady rate for FM-A laser (first time!) and FM-B. But last attempt on FM-A proved to be quite stable.

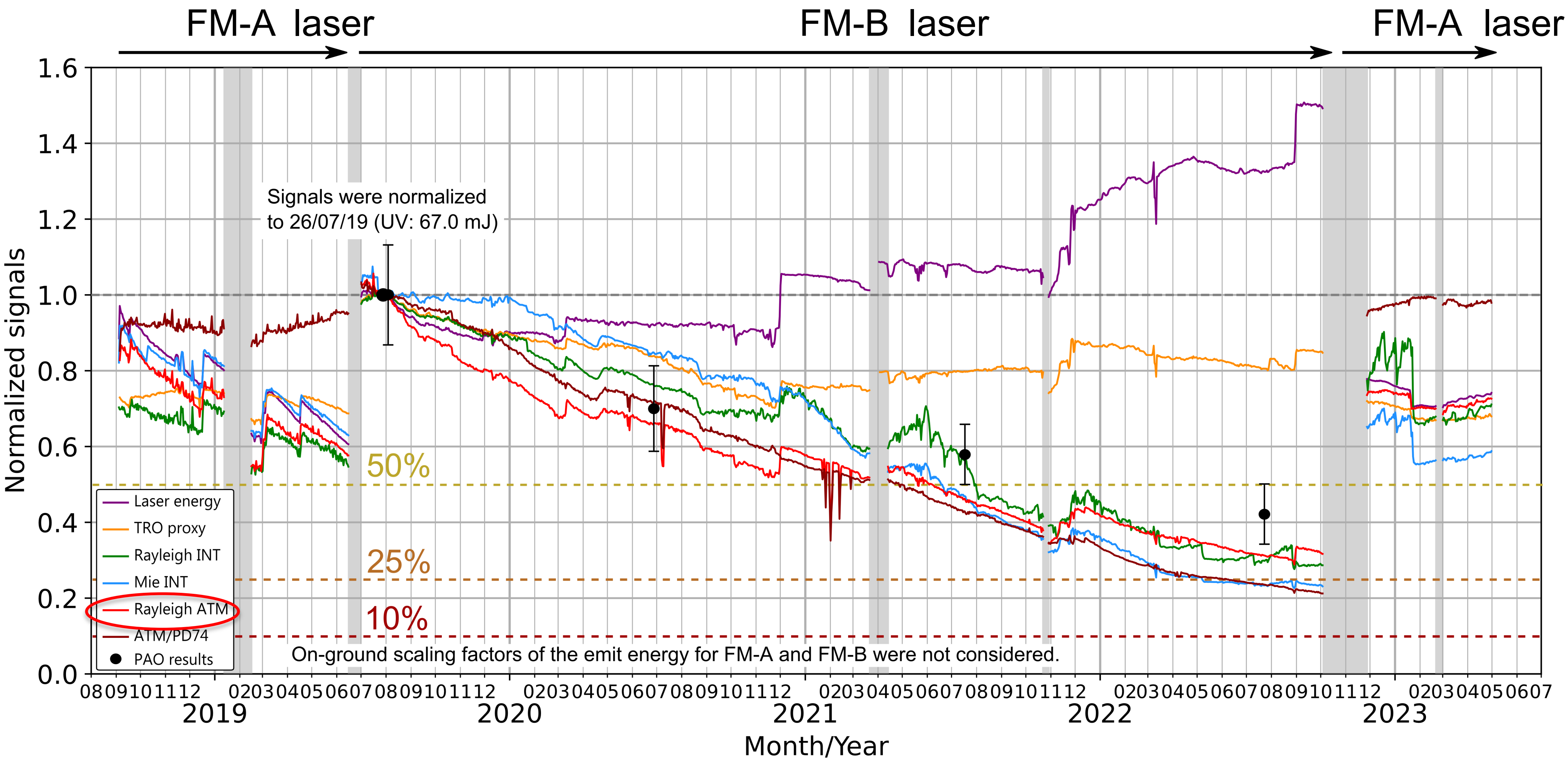
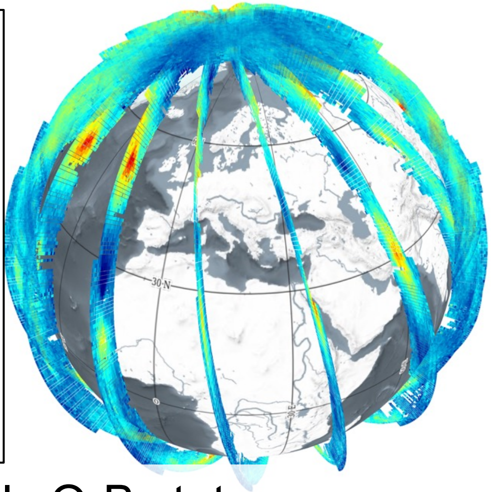


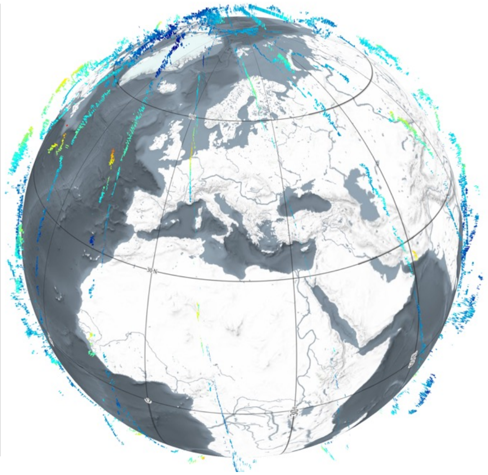
Figure by O. Lux, DLR

Aeolus Level-2B HLOS (horizontal line-of-sight) wind data quality

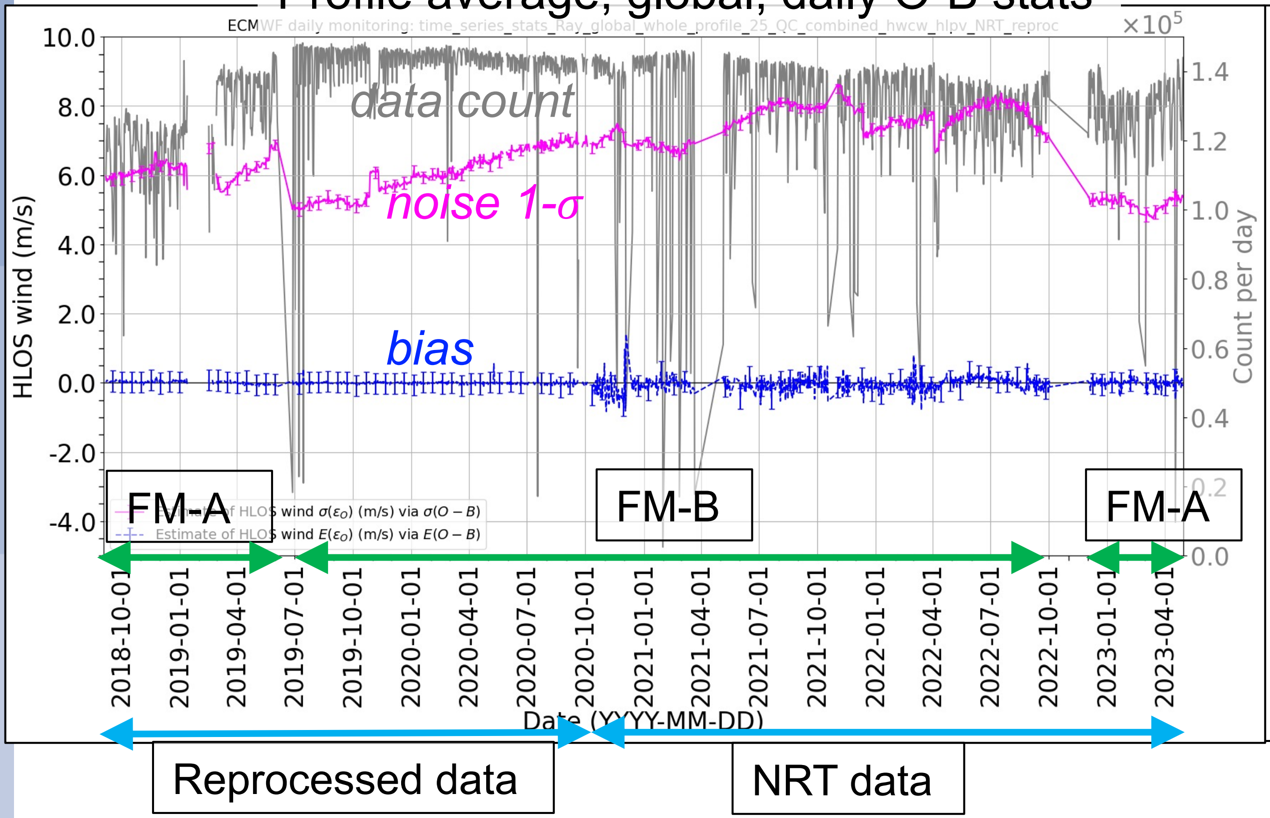
Rayleigh-clear
- Large variability of random errors (variable signal levels)
- Recent ***NRT*** FM-A laser good (best processing, reduced readout noise, reasonable signal)

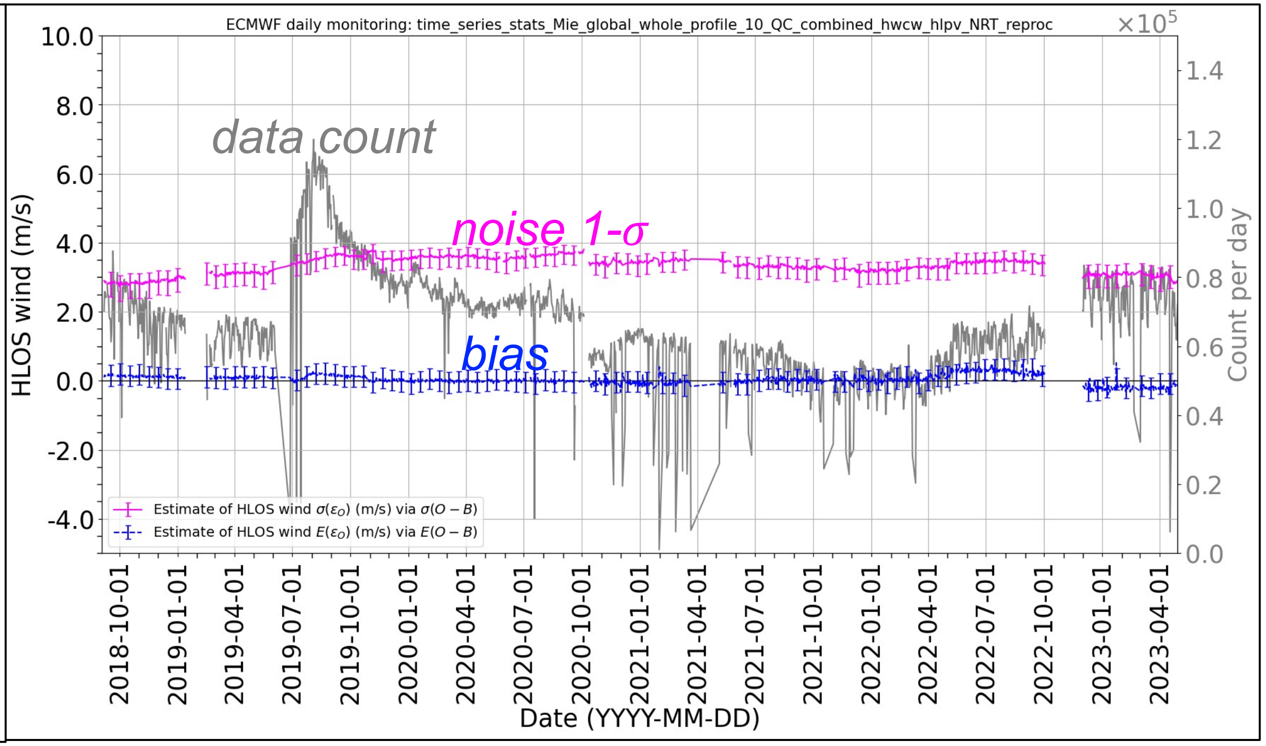


Mie-cloudy
- Noise **quite stable and small** compared to Rayleigh-clear
- But data count variable with signal levels/aerosol load



Profile average, global, daily O-B stats





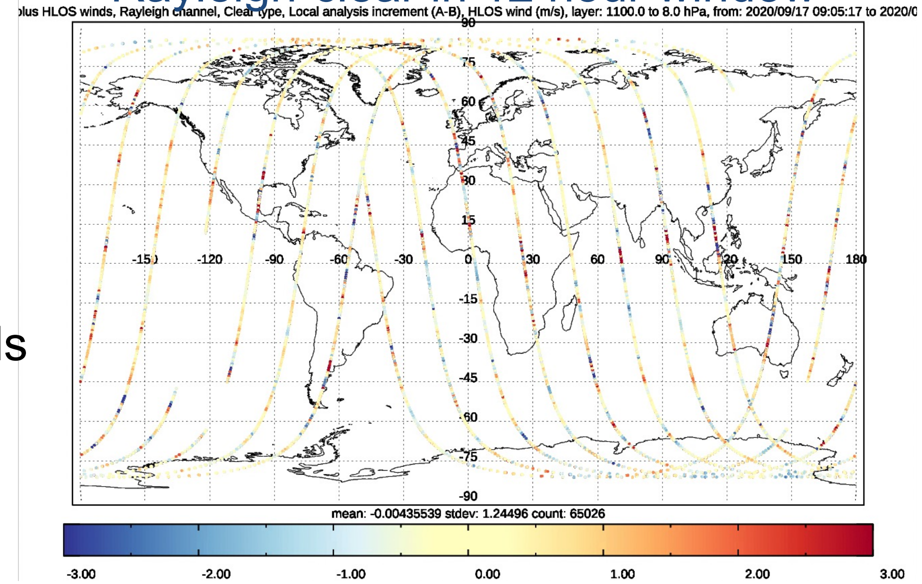
Aeolus NWP impact at ECMWF

Methods for Aeolus L2B wind NWP impact assessment at ECMWF

- **O**bserving **S**ystem **E**xperiments (OSEs):
  - For robust assessment of impact into the medium-range
  - 2nd reprocessed FM-B period (**OSE for long period**):
    - Rayleigh-clear + Mie-cloudy as in current operations; **29 June 2019 to 9 October 2020**
    - $T_{CO}639$ model resolution (~18 km)
- **F**orecast **S**ensitivity **O**bservation **I**mpact (FSOI):
  - Assessment of short-range forecast impact – with some limitations
  - Operational FSOI; since 9 January 2020
  - FSOI via 2nd reprocessed dataset OSE (Aeolus "on" experiment)

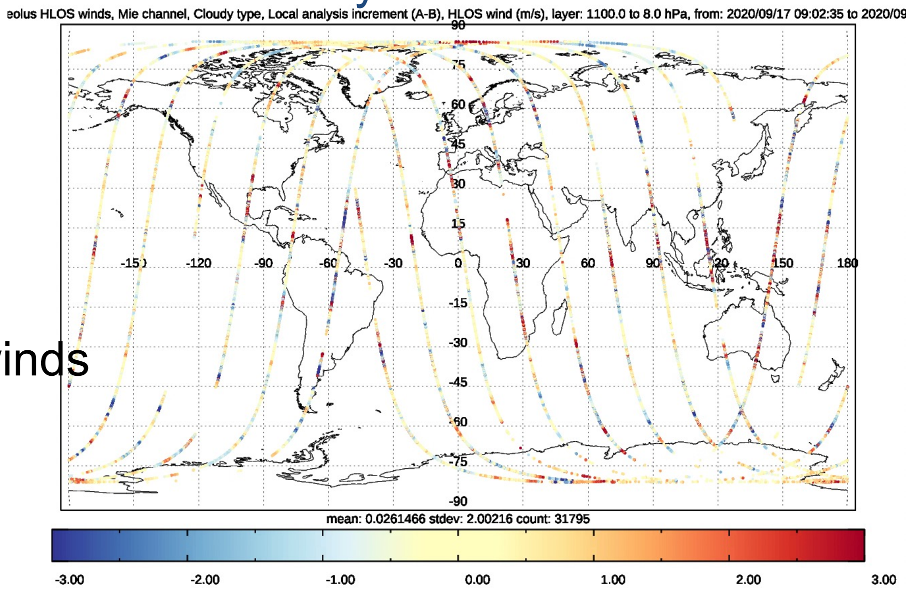
Rayleigh-clear in 12 hour window

65k winds



Mie-cloudy in 12 hour window

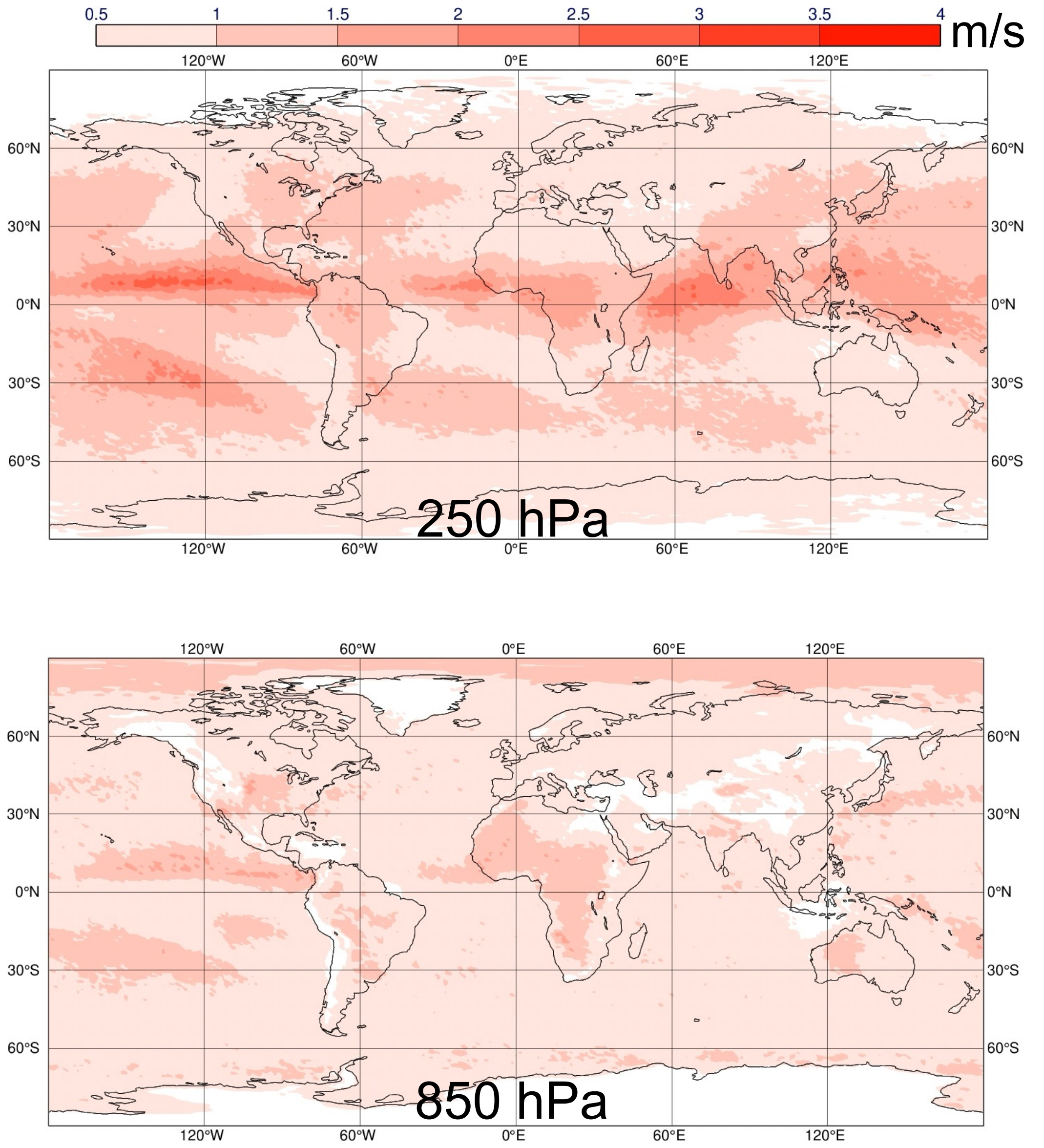
32k winds



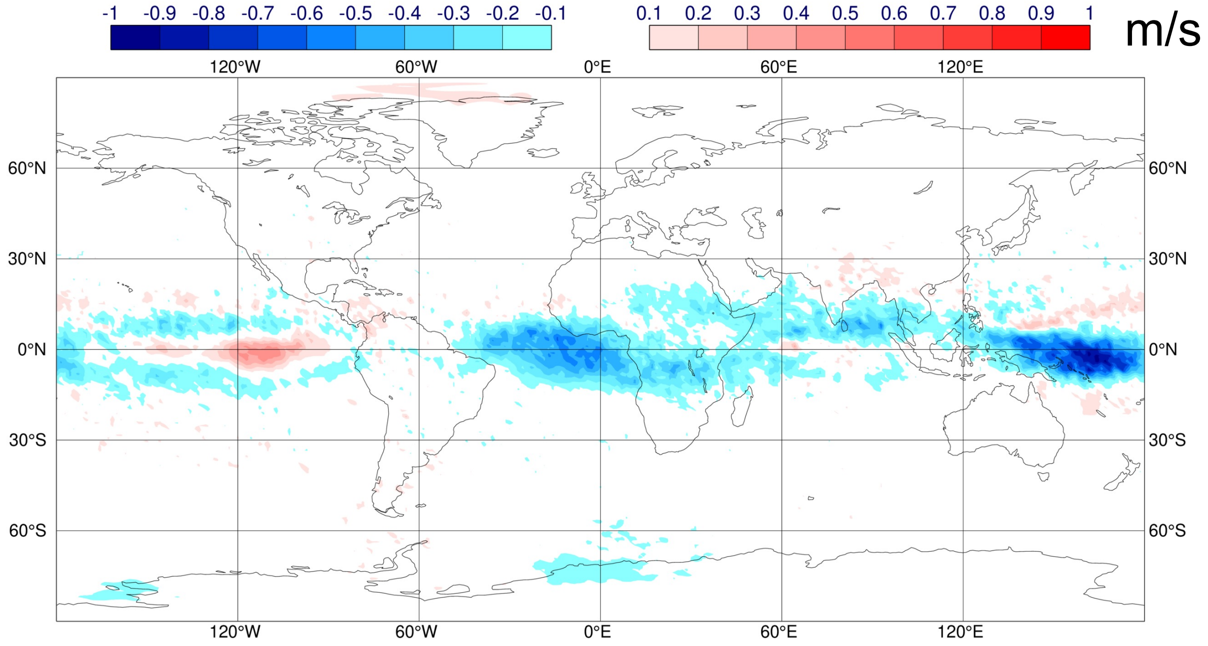
A-B

Assimilating Aeolus winds has strong effect on zonal wind analyses

Standard deviation of differences in u analysis



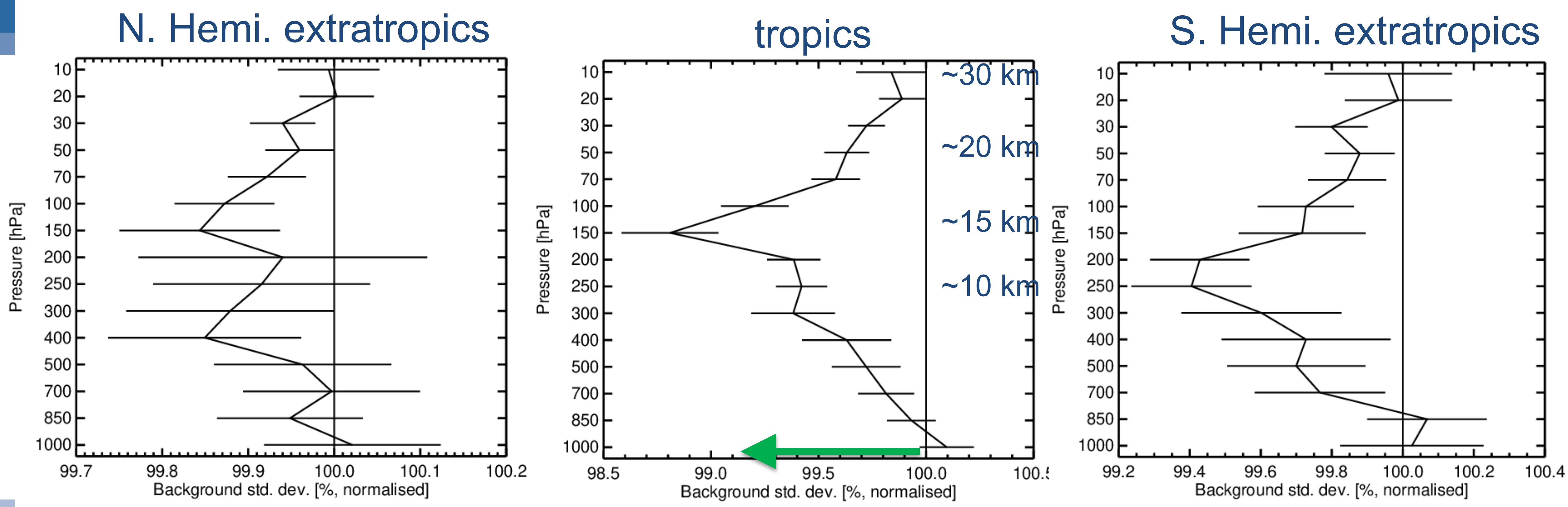
Mean difference in u analysis at **100 hPa**



Largest changes made to tropical upper troposphere and SH extratropics – in climatological **convergence zones**; larger background wind errors associated with convection

Independent wind observations confirm improvements from assimilating Aeolus

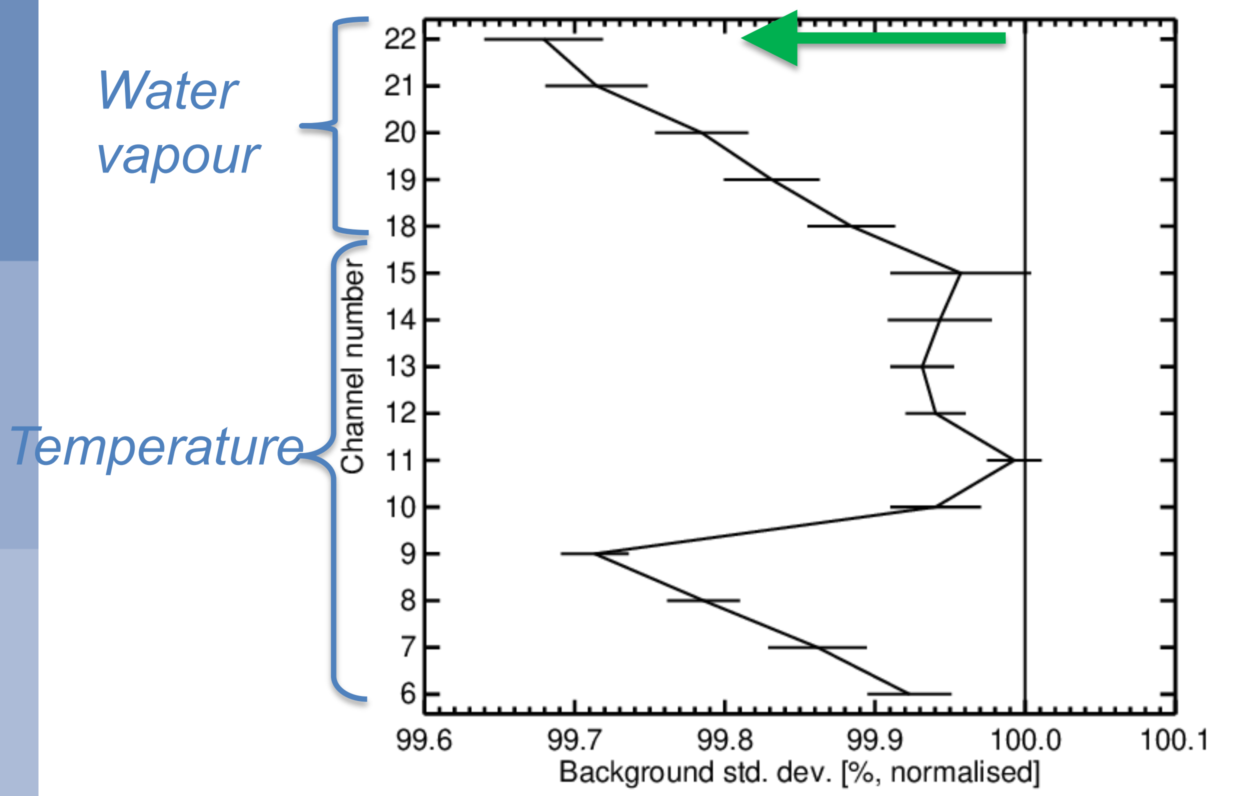
Fit to vector wind from aircraft, radiosondes and radar wind profilers



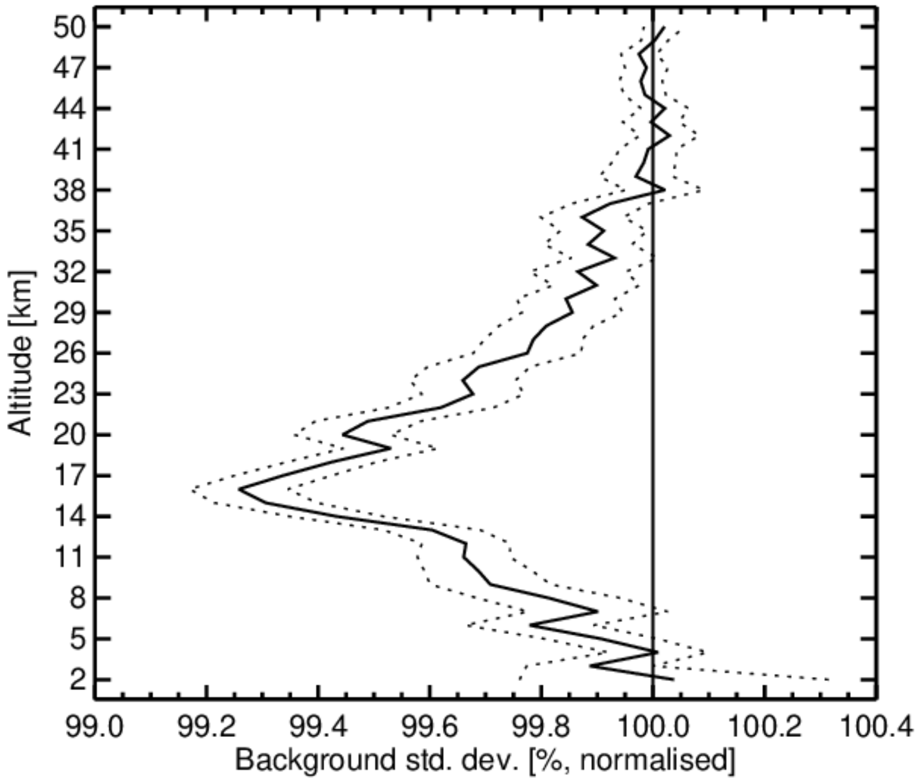
Positive impact in mid-troposphere to lower stratosphere
Largest impact on **wind in upper troposphere and lower stratosphere in tropics**

Improved winds lead to better NWP temperature and humidity forecasts

Global, ATMS (microwave radiances)



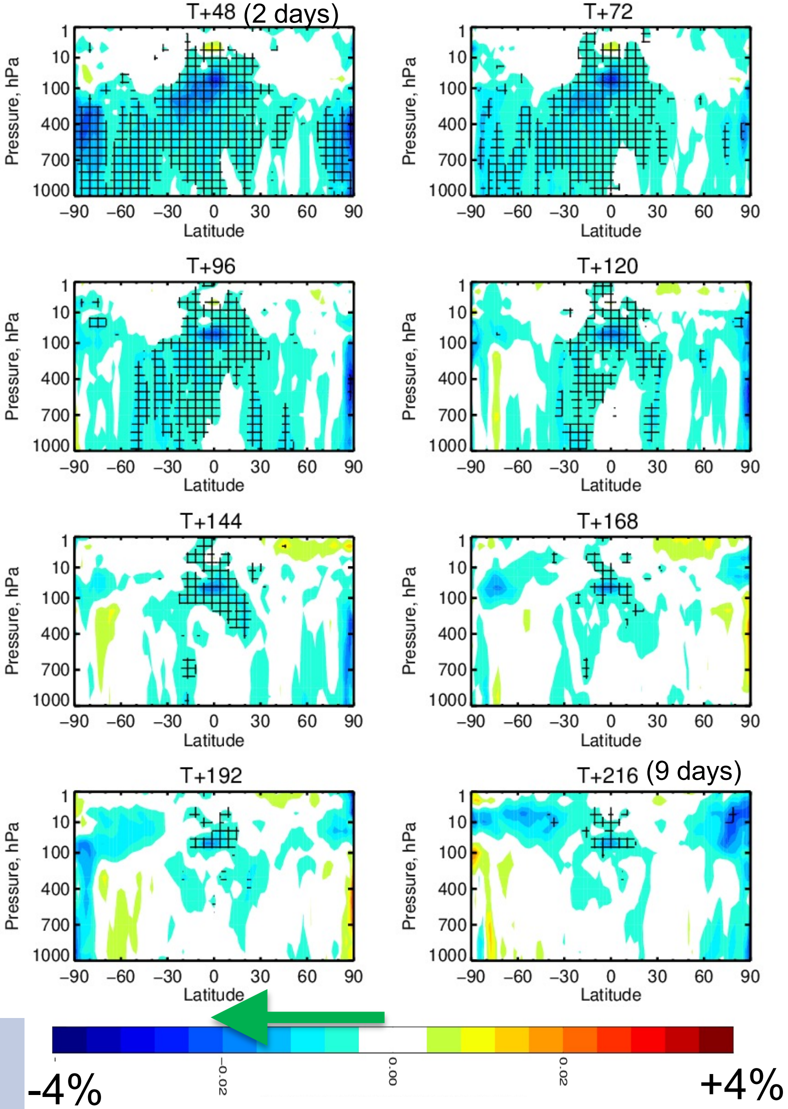
Global, GNSS radio occultation (bending angles)



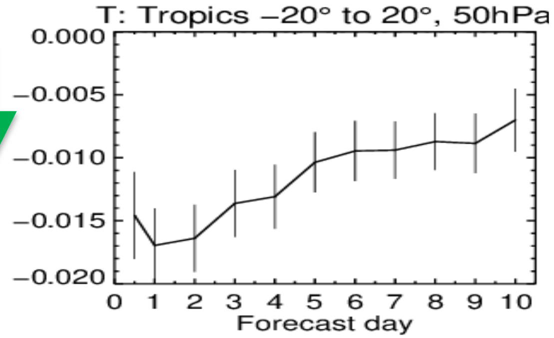
Positive impact on **temperature** and **humidity**
Strongest in **upper troposphere/lower stratosphere**

Aeolus significantly improves NWP forecasts in most areas and forecast ranges

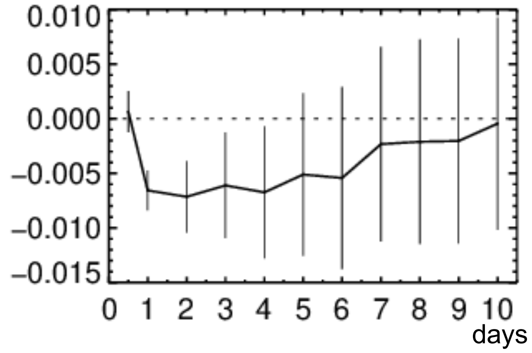
Vector wind RMSE zonal average



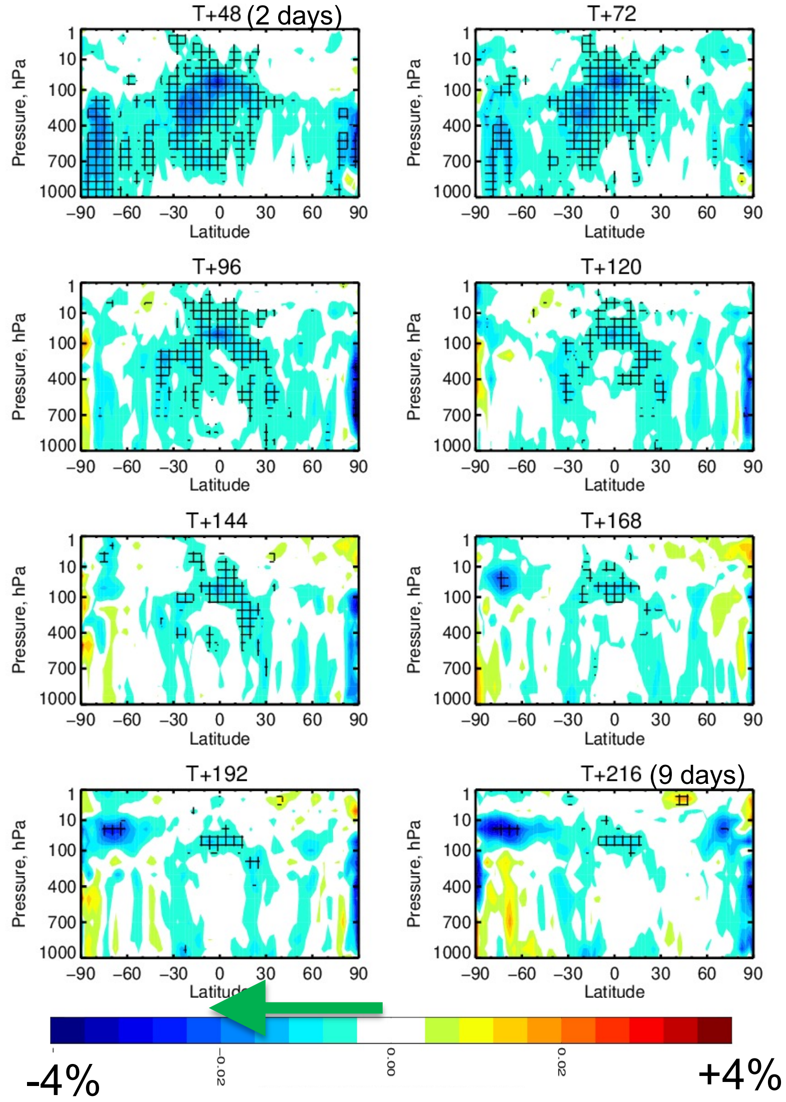
Strongest impact in tropics lower stratosphere (~20 km)



Even N Hemi. Z500 improved significant to day 4

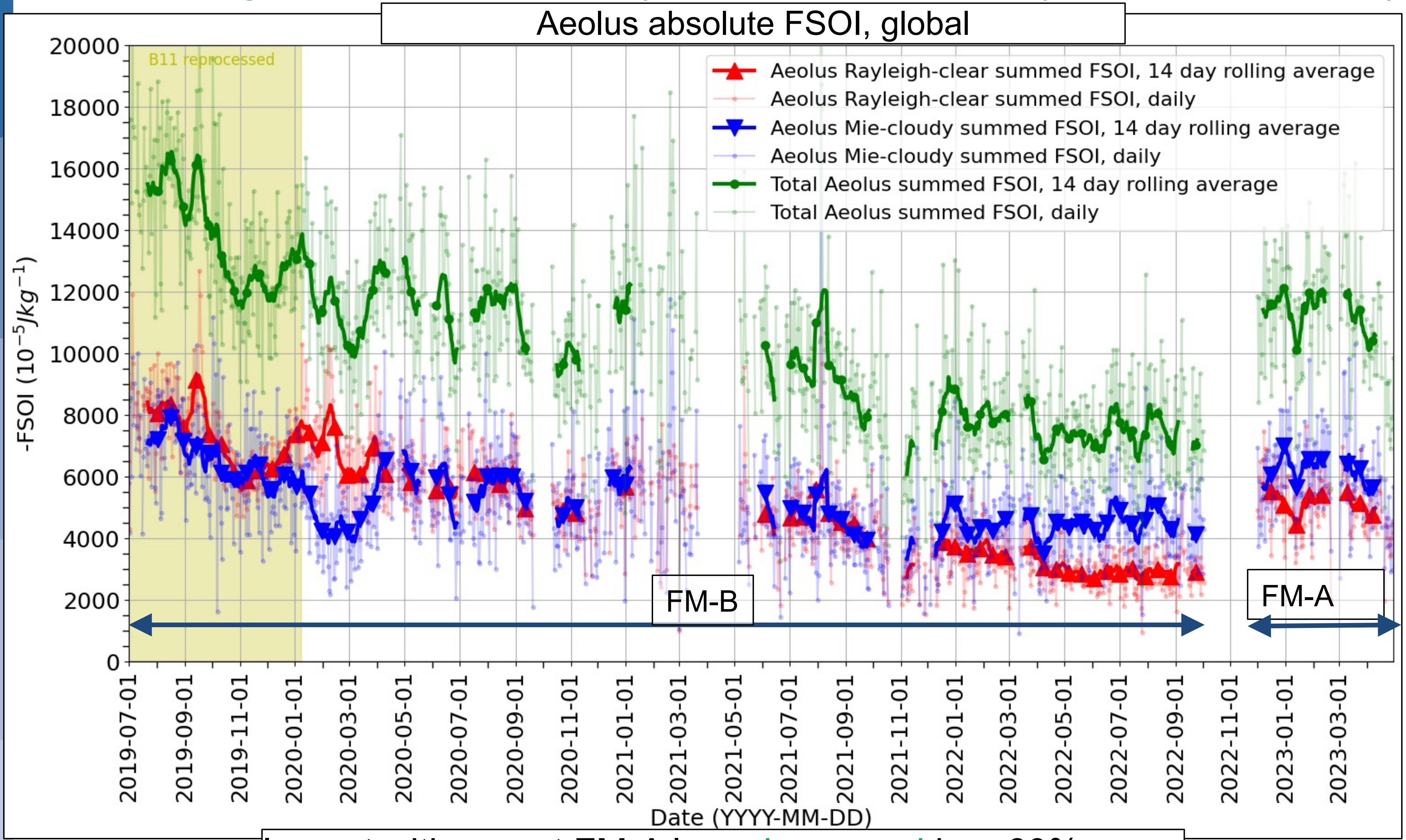


Temperature RMSE zonal average



Positive impact – good magnitude for one satellite instrument

Short-range forecast impact by **F**orecast **S**ensitivity to **O**bservation (FSO) time-series

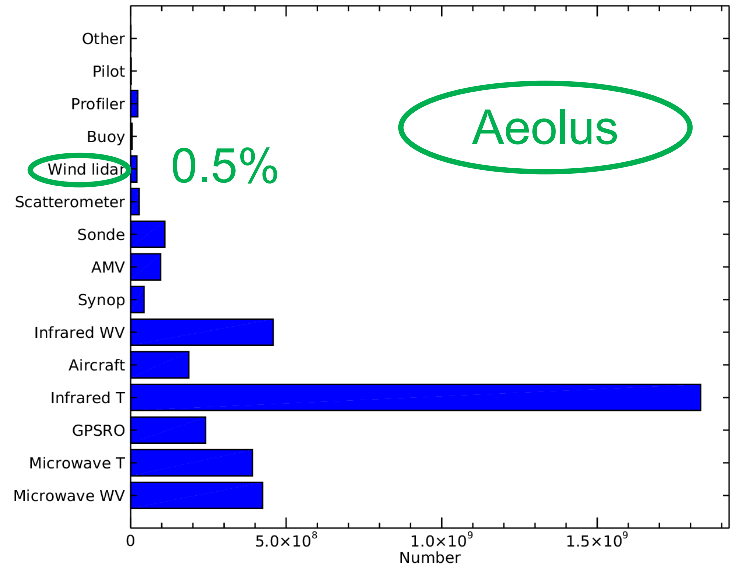


- Impact depends on random error and amount of data used (data gaps, QC)
- Impact was boosted by increased signal levels of FM-A near end of life

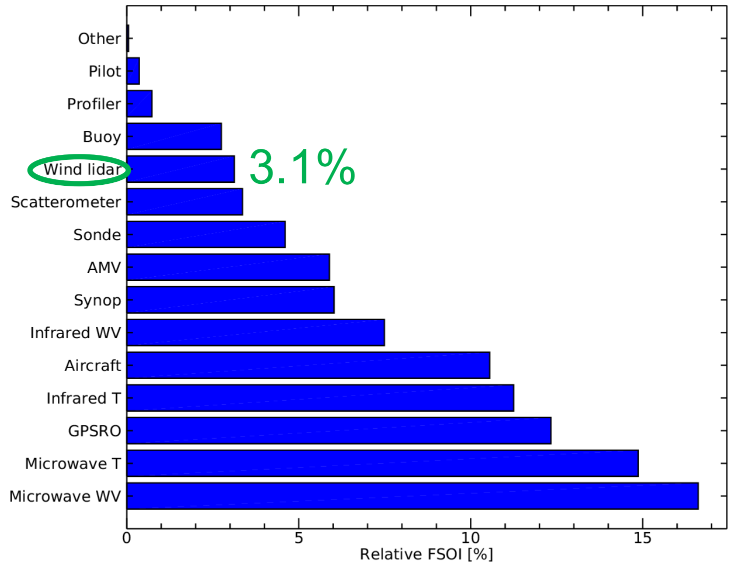
Impact with recent FM-A laser increased by ~60% compared to ***end*** *of FM-B – thanks to better signal*

ECMWF recent operational relative FSOI (1 Jan to 30 April 2023)

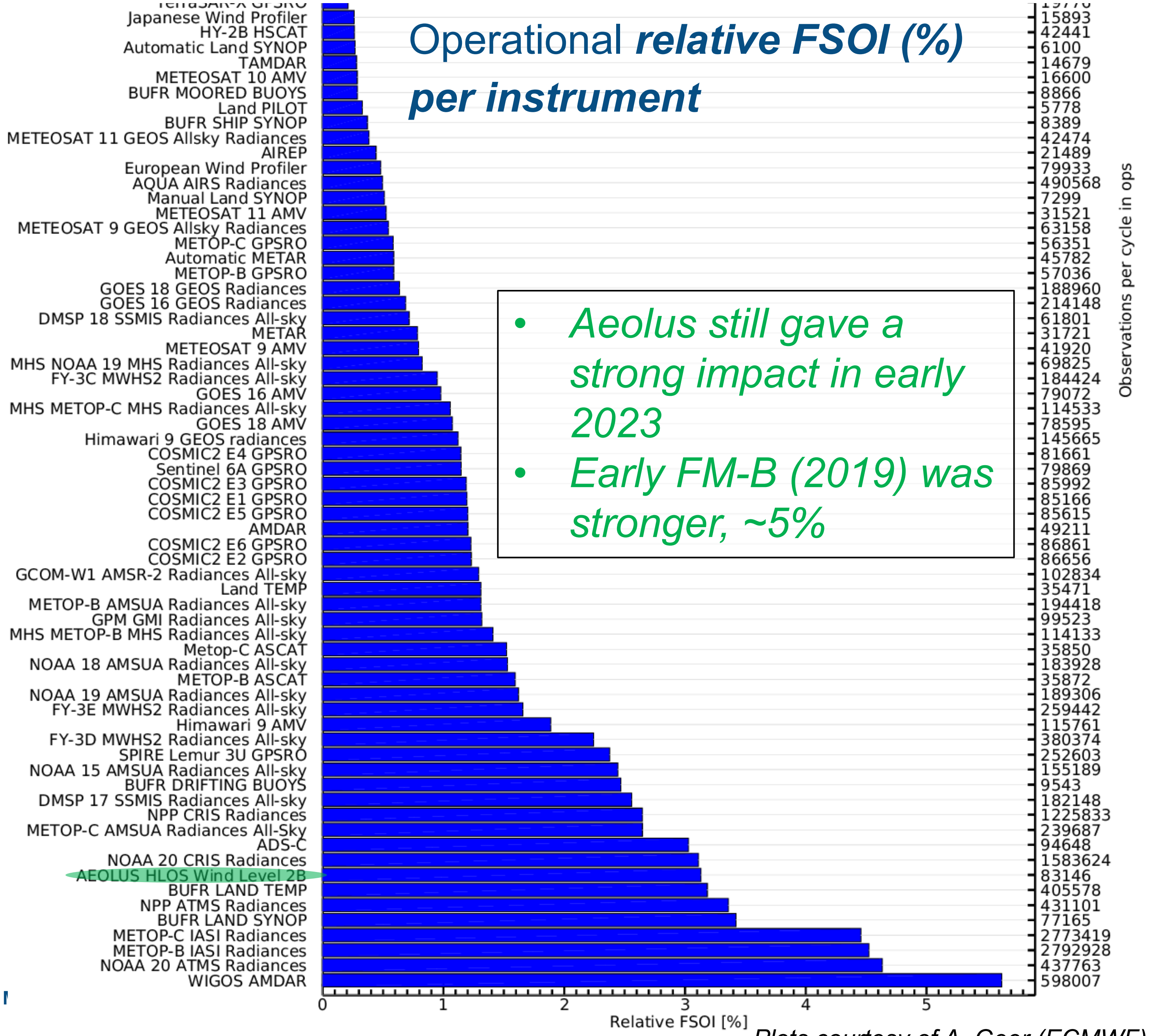
Data counts by group



Relative FSOI (%) by group



Operational *relative FSOI (%)* *per instrument*

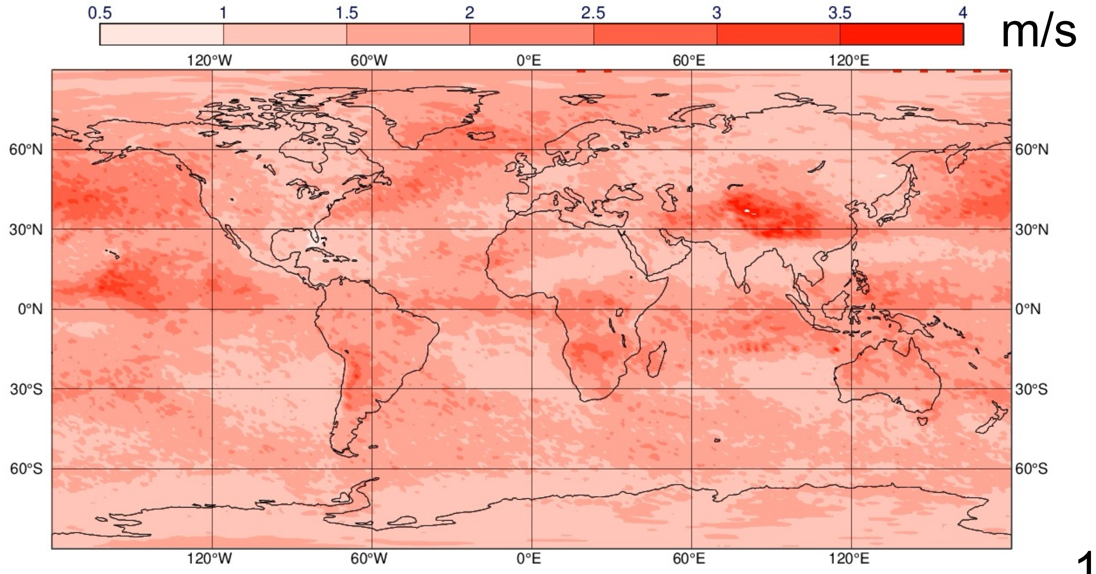


- *Aeolus still gave a strong impact in early 2023*
- *Early FM-B (2019) was stronger, ~5%*

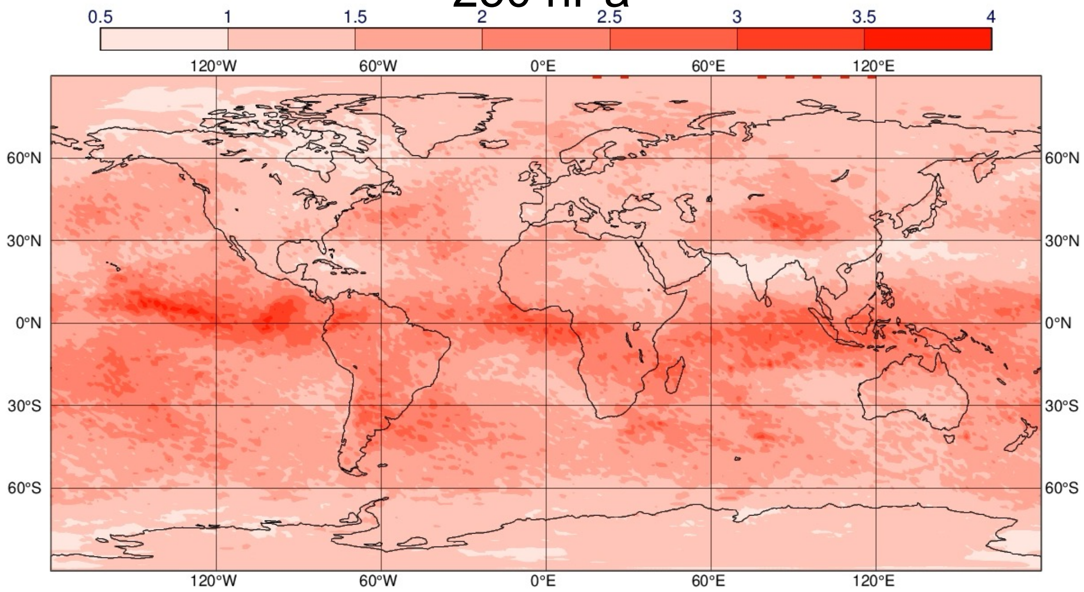
Plots courtesy of A. Geer (ECMWF)

An impression of analysis u-component wind **random errors**: stdev of **ECMWF minus Met Office** analysis differences: 1 Jan to 20 Feb 2023

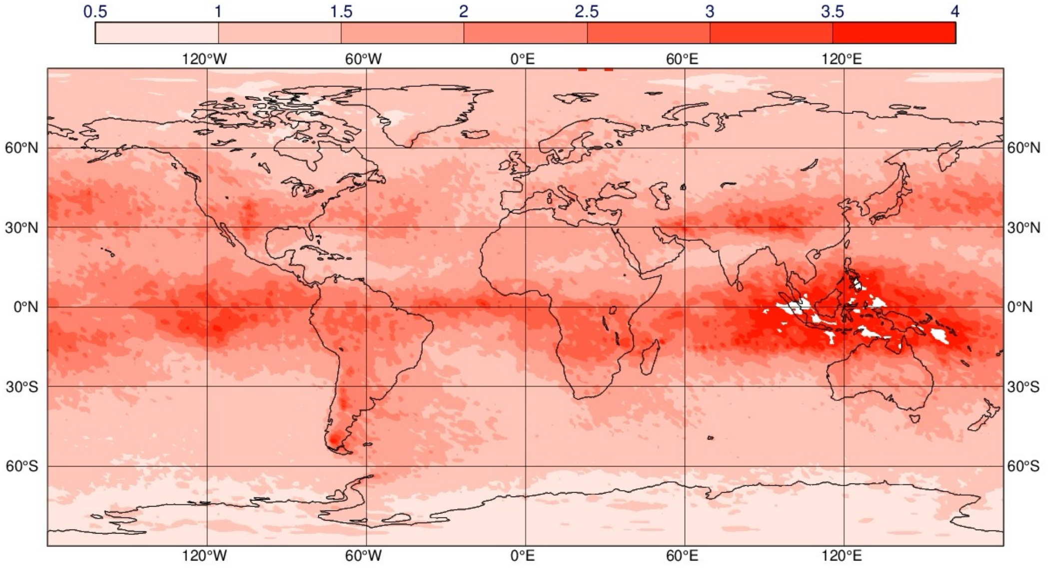
500 hPa



250 hPa



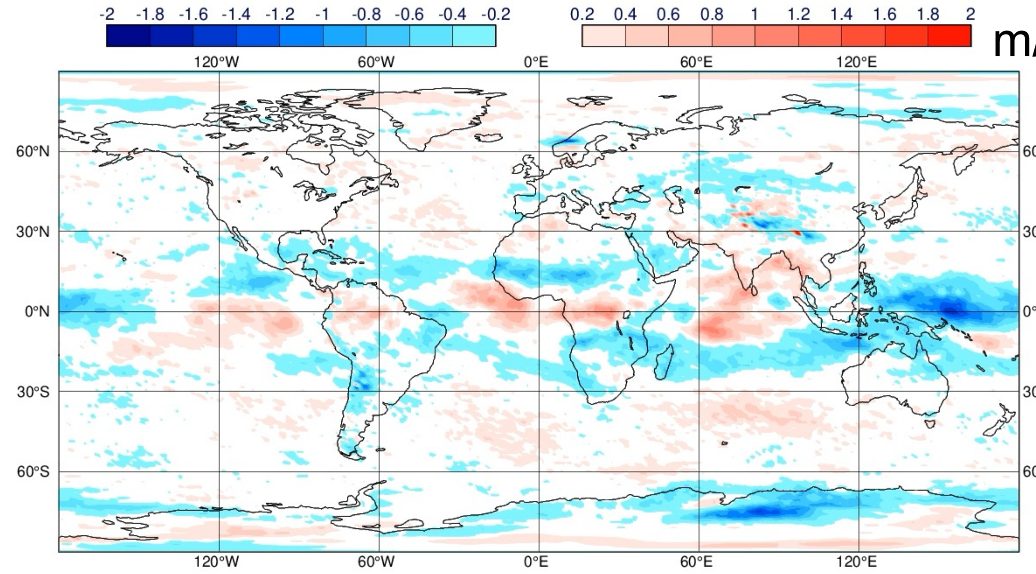
100 hPa



NWP *analyses* of wind are still quite uncertain in tropics/oceans; random errors ~3 m/s

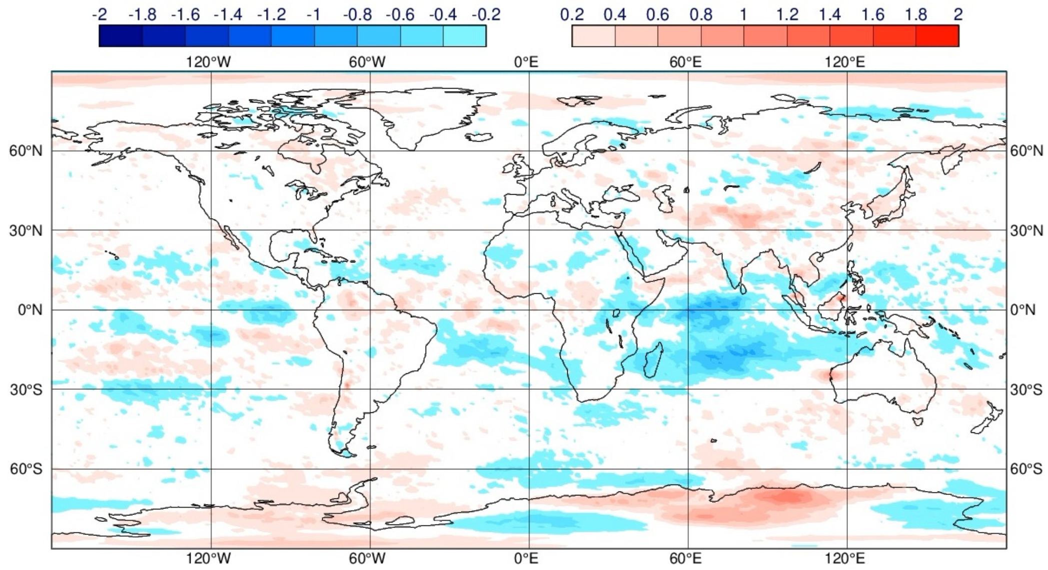
Can estimate 1σ of u-error of ECMWF analysis, by multiplying by $\frac{1}{\sqrt{2}}$~0.7 (assuming similar random error for ECMWF and MO)

An impression of analysis u-component wind **systematic errors**: mean of **ECMWF minus Met Office** analysis differences: 1 Jan to 20 Feb 2023

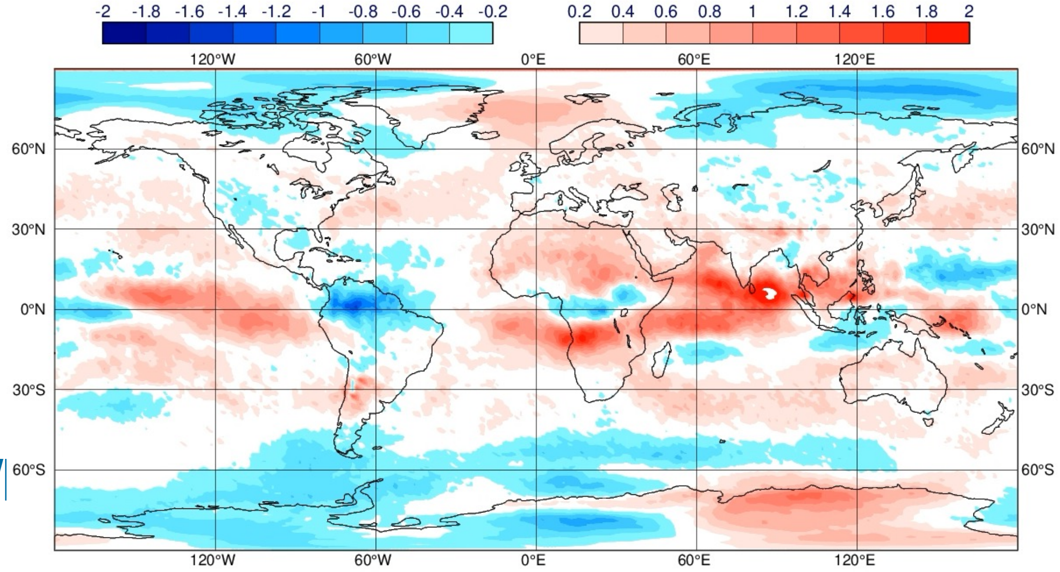


m/s

500 hPa



250 hPa



100 hPa

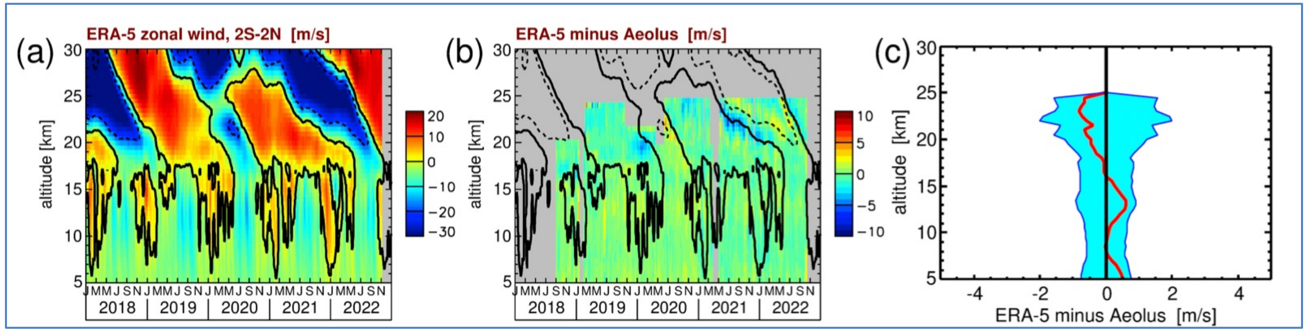
NWP *analyses* of wind are still quite uncertain in tropics/oceans; biases of 1-2 m/s

ECMWF

Some other demonstrated benefits in atmospheric sciences from Aeolus

- Applications in atmospheric dynamics research:
  - gravity waves, equatorial waves, SSW events, QBO monitoring – improving understanding of Earth's climate

https://doi.org/10.5194/egusphere-2023-408



- Optical properties used in atmospheric composition research:
  - Wildfire smoke, Saharan dust, volcanic eruption plumes, atmospheric composition data assimilation
  - Unique ability of Aeolus to **measure dynamics and optical properties** should be exploited further – coupled composition and dynamics forecasts
  - Cloud properties. *Exploitation of Aeolus cloud information in NWP has not yet been done*

- Aeolus winds are useful for verifying/improving usage of other satellite wind observation types e.g. **A**tmospheric **M**otion **V**ectors and checking if other observation types are improving wind

Summary on Wind Information from Aeolus

- A novel technology was required to actively sense wind profiles from space and this was demonstrated with the Aeolus Doppler Wind Lidar
- Measured signals have a reasonably direct link to the geophysical variable
- Positive NWP impact corroborates dynamical reasoning on the **importance of vertically resolved wind** profiles e.g. larger impact in tropics, and complementary to some other components of the Global Observing System i.e. vertical resolution
  - Wind field is still not that well constrained in analyses
- Applications found beyond NWP, in atmospheric research

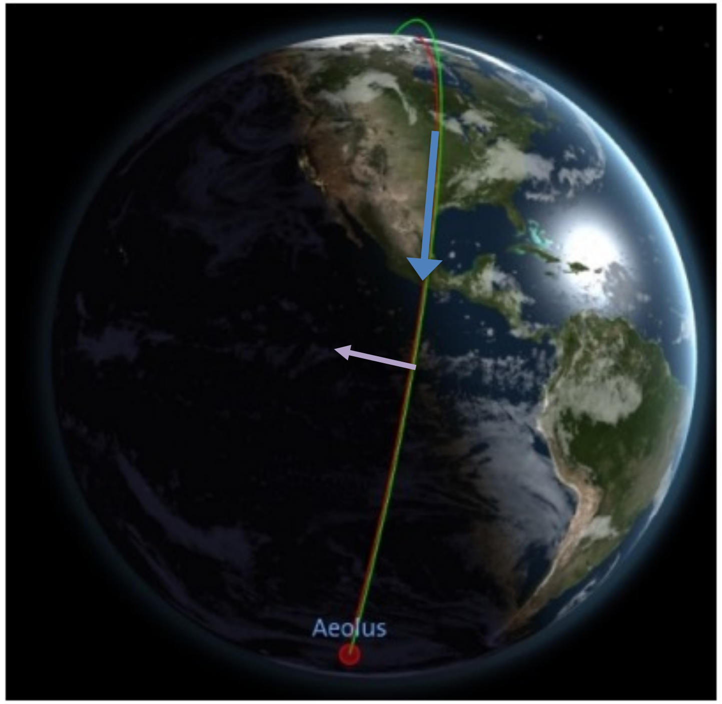
- **Future:**
  - After mission, focus shifts to achieving best quality data with reprocessing for research/reanalysis and best possible assimilation methods
  - An **operational follow-on mission (EPS-Aeolus)** with two satellites (one after other) in 2031 time-frame is in early preparation phase at ESA/EUMETSAT – *decision by EUMETSAT member states in 2025*
    - *Many improvements planned relative to Aeolus – so potentially larger impact*

Thanks for listening. Any questions?

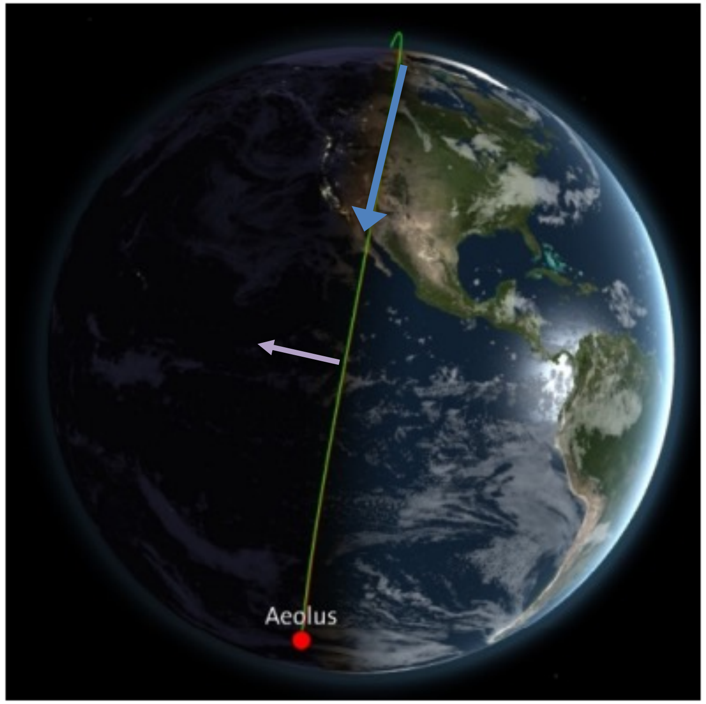
Backup slides

Aeolus’ orbital parameters

Aeolus track in July



Aeolus track in October



- Dawn-dusk sun synchronous (18:00 ascending node)
- 7 day repeat cycle (111 orbits)
- Inclination: ~97 degrees
- Altitude: ~320 km
- The laser points towards the dark side of the terminator to reduce UV solar background noise – but this can’t be avoided over the poles in summer

Types of Doppler wind lidar

- Coherent detection
  - Detecting beat signal mixing of returned signal with internal reference
  - Particulate (Mie) scattering only
- **Direct detection:**
  - Aeolus uses this
  - Measurement is *signal intensity* (or *photon counts)* through optical filters (interferometers) which varies with the frequency of light
  - Molecules *and* particles are the source of the backscattered signal
    - Useful for NWP to have both clear air + cloud/aerosol winds

Aeolus Rayleigh channel

Uses "filter method", specifically the double-edge technique

- Two frequency filters (A and B) sample sides of Rayleigh-Brillouin spectrum, providing photon counts
- Contrast function (response) calculated from counts: $\boldsymbol{R} = \frac{\boldsymbol{A}-\boldsymbol{B}}{\boldsymbol{A}+\boldsymbol{B}}$
- *R* is measured for both internal reference (i.e. outgoing laser spectrum) and for atmospheric return
- Calibration is needed for both internal and atmospheric responses to relate response to frequency
- Change in frequency of atmospheric relative to internal frequency is obtained $\Delta\boldsymbol{f} = \boldsymbol{f}_{\boldsymbol{atm}} - \boldsymbol{f}_{\boldsymbol{int}}$ i.e. the Doppler shift, hence LOS wind

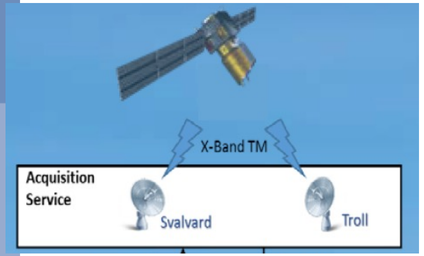
Aeolus Mie channel

Wind derived from the narrow Mie spectrum obtained by "Fringe Imaging Technique"

- Position of interference pattern (called a "fringe") is related to frequency (by calibration), both for the internal and atmospheric returns
- Measured fringe centroid for both internal and atmospheric signals is then converted to frequency, hence calculate $\Delta \boldsymbol{f} = \boldsymbol{f}_{\boldsymbol{atm}} - \boldsymbol{f}_{\boldsymbol{int}}$ i.e. the Doppler shift, hence LOS wind

How Aeolus products were produced in NRT

Wind products were produced in NRT for the benefit of operational NWP – *despite being only a demonstration mission*



Raw satellite telemetry

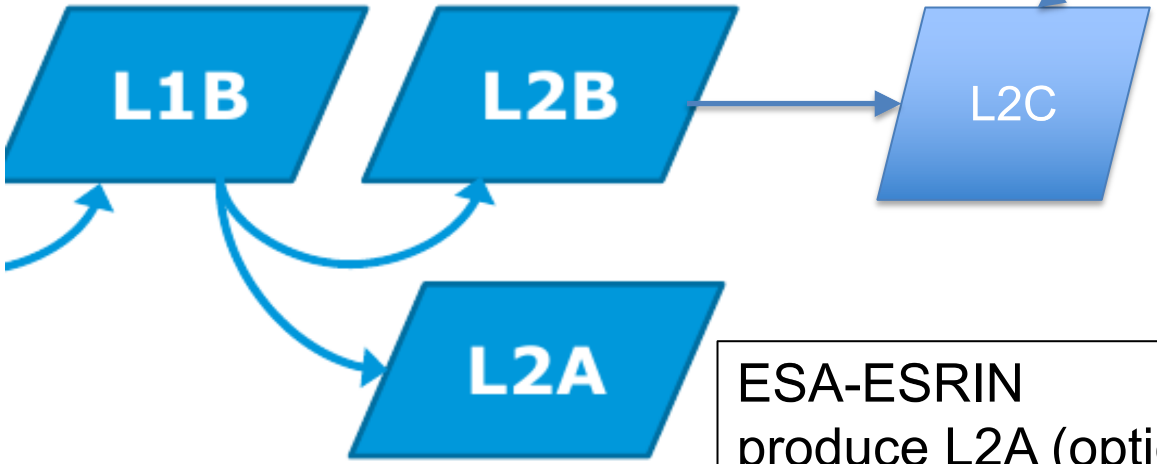
L0 and L1A data

ESA-ESRIN produce **Level-1B** data (calibrated signal levels)

Level-2B wind product (aimed at NWP); produced by **ECMWF**

ECWMF data assimilation analysis

L2B BUFR files from ECMWF sent to EUMETSAT for distribution on GTS/EUMETCast

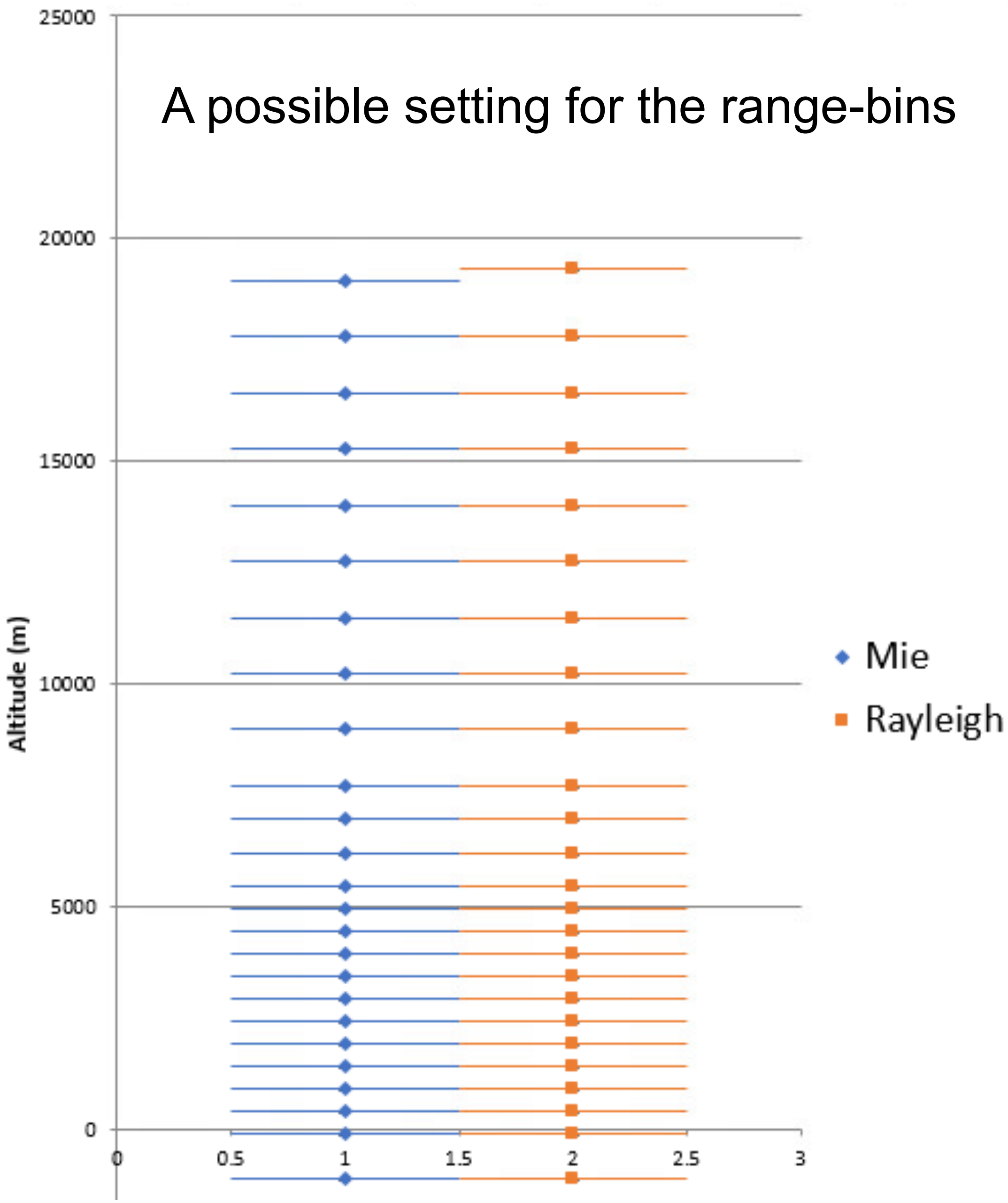


ESA-ESRIN produce L2A (optical properties) product

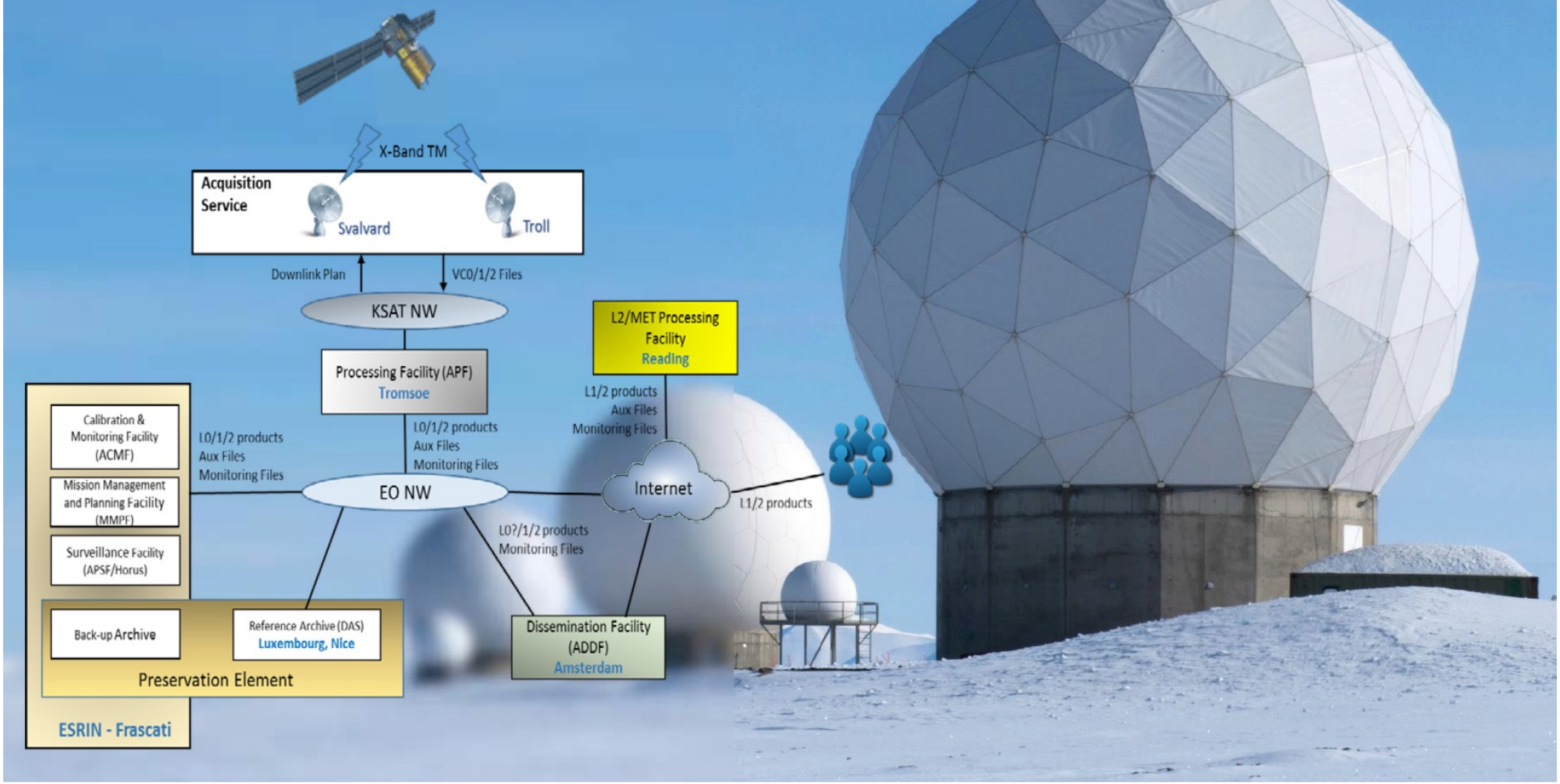
L2B processing algorithms developed mostly by KNMI, ECMWF, Météo-France, DLR and DoRIT

There are 24 vertical range-bins to assign

- Range-bin thickness can vary from 0.25 to 2 km thick in 0.25 km increments
- Rayleigh and Mie range-bin settings can be different
- Range-bins settings can vary according to latitude/longitude boxes that are defined on-board the satellite
  - An attempt has been made to optimise the settings for NWP impact – varying with latitude



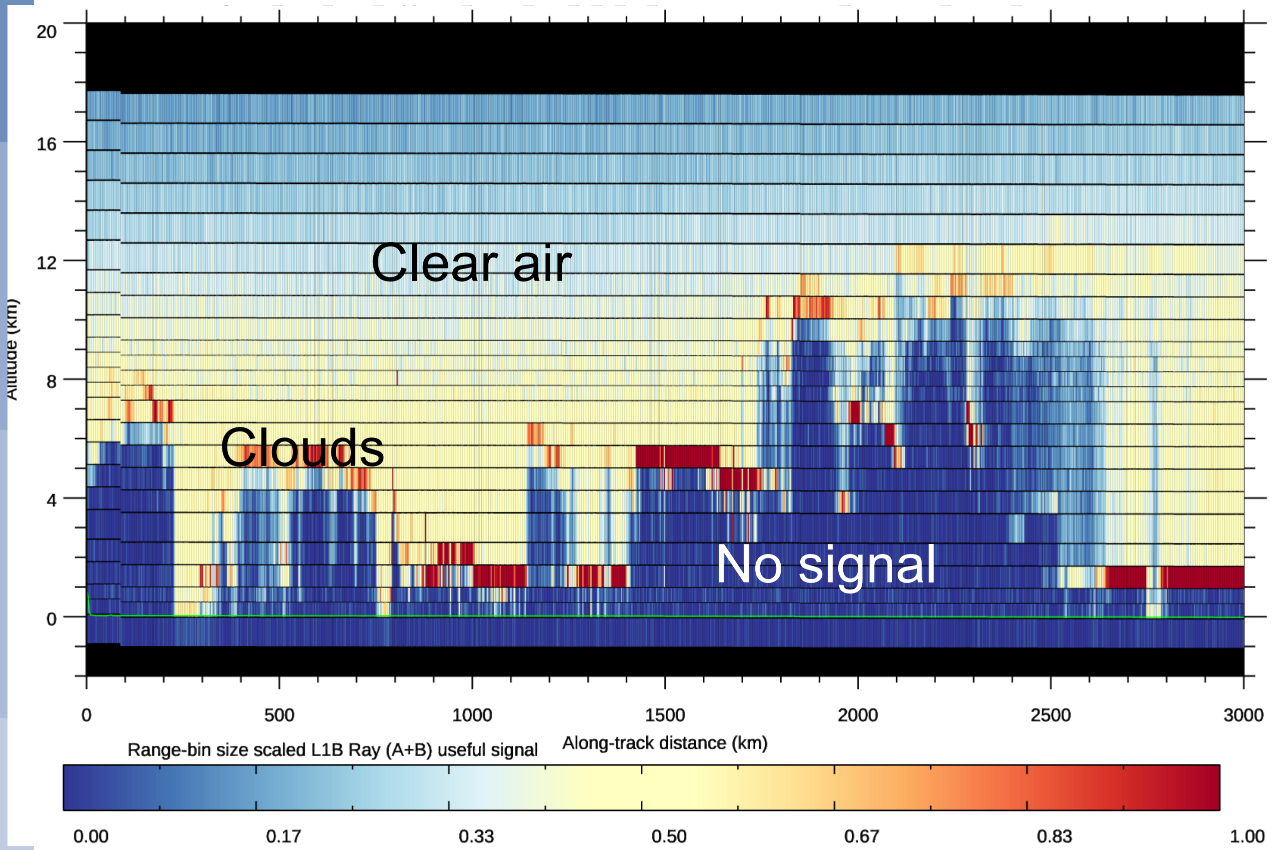
Aeolus Payload Data Ground Segment



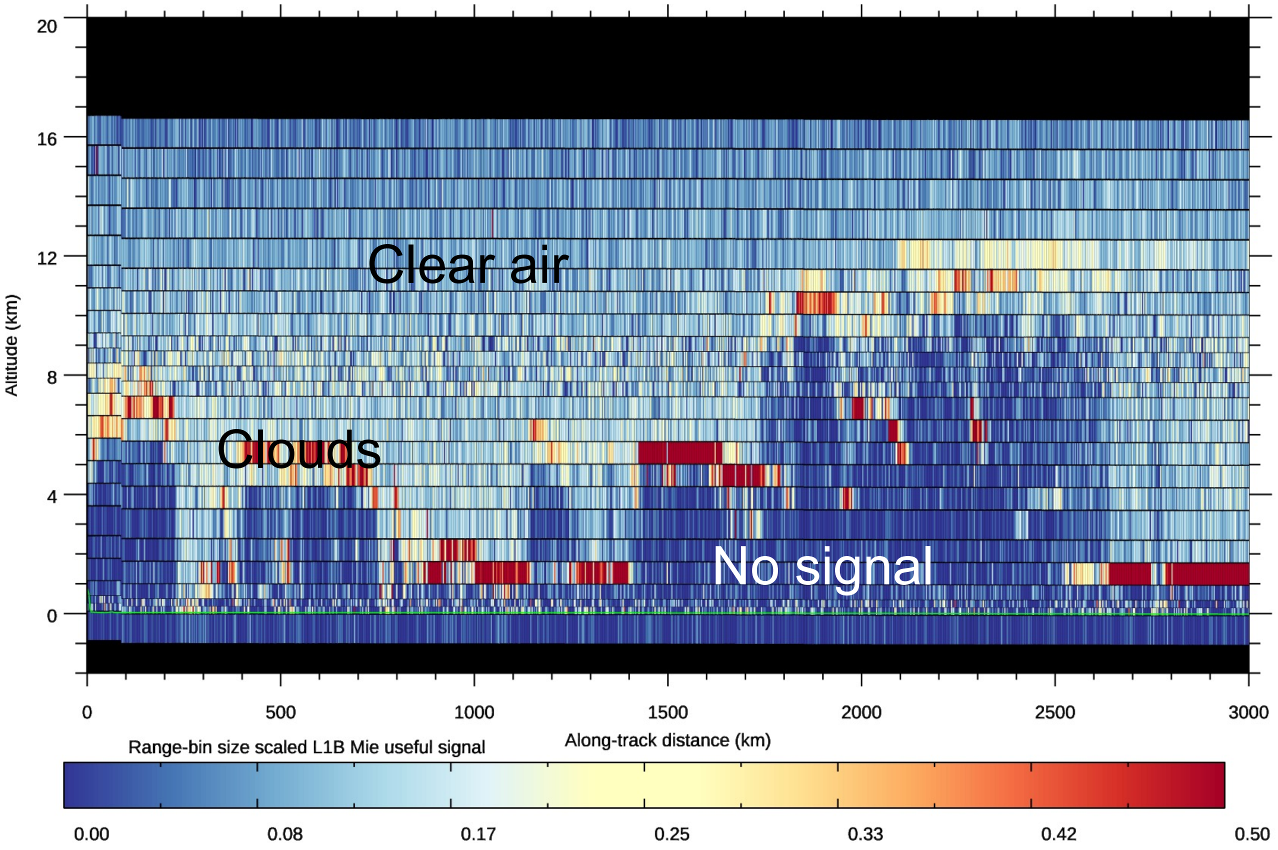
Example of Level-1B signal amplitude (photon counts, i.e. *not winds)* for a 3000 km stretch of data

Each data point is ~2.7 km across (a flexible instrument setting)

Rayleigh channel signal



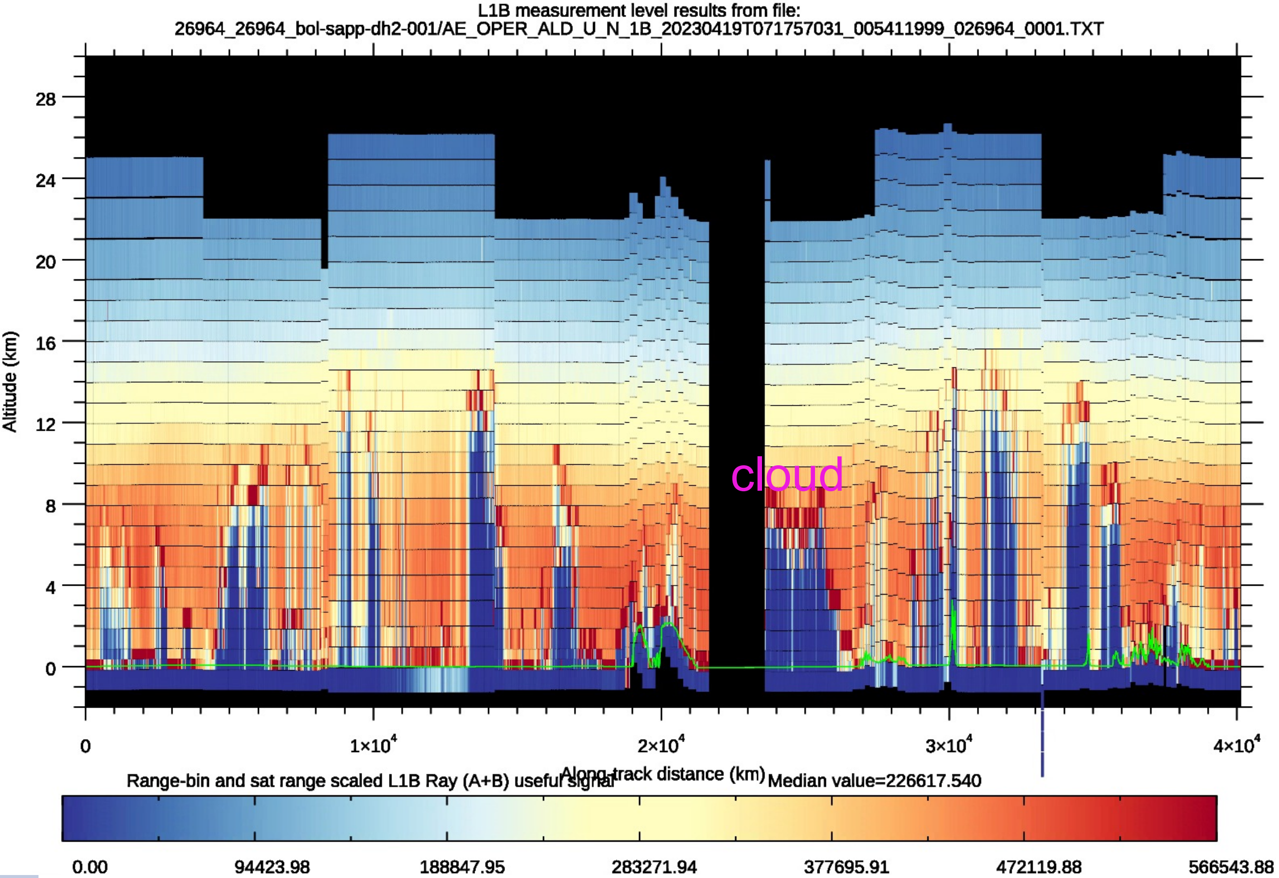
Mie channel signal



Satellite moves at ~7.3 km/s to sweep out this lidar "curtain"

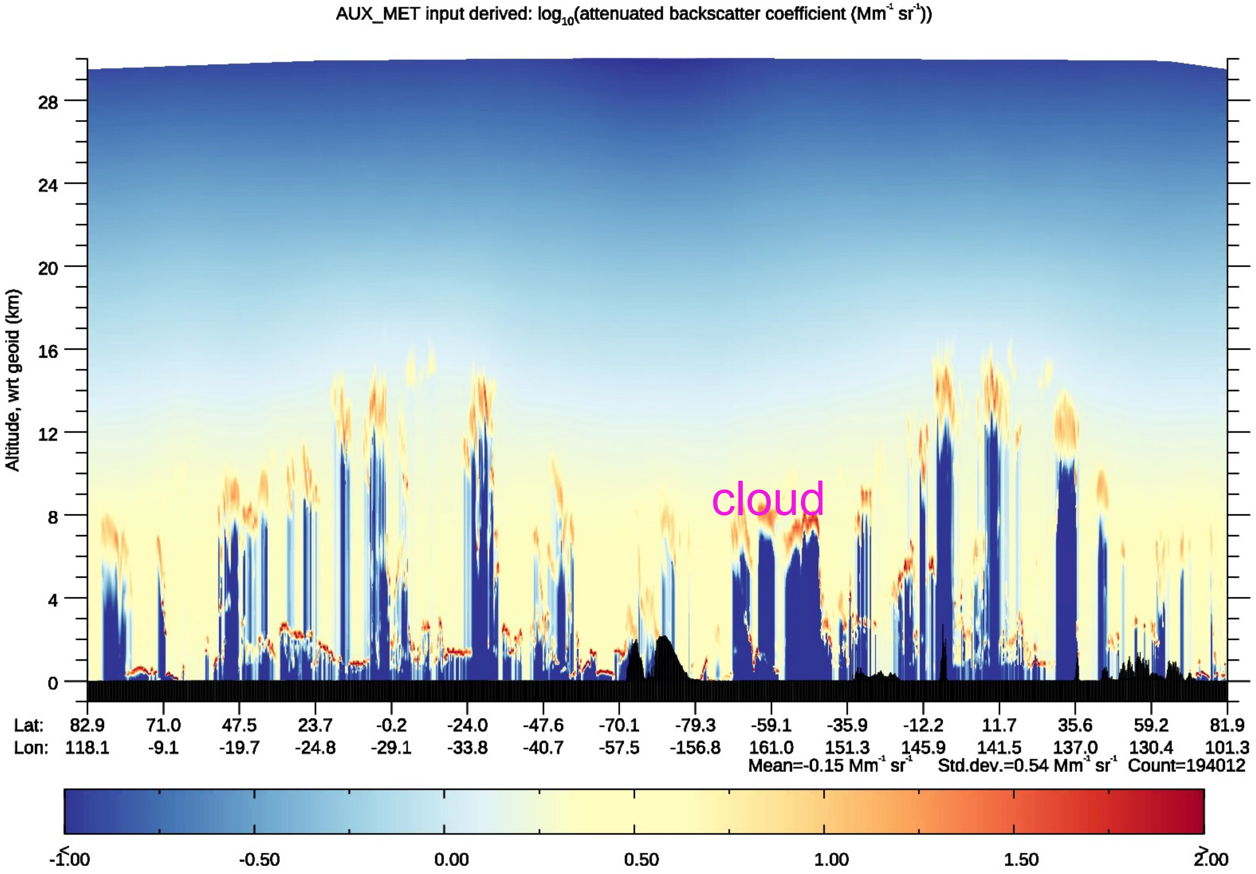
Real Aeolus measurement signal amplitudes

Aeolus L1B signal levels on Rayleigh channel



24 vertical range-bins are evident

ECMWF “forward modelled” attenuated backscatter



Level-2B wind processing algorithm overview

- Line-of-sight (**LOS**) or **H**orizontal **LOS** wind components suitable for use in NWP/research
  - Using measurement-level L1B data and calibration products
- Enhancements compared to L1B observations:
  - **Grouping of measurements**: control of horizontal resolution and noise
  - **Classification of measurements**: into different **types** using optical properties (clear/cloudy); to avoid significant Mie contamination of Rayleigh
  - **Accumulation**: of L1B signal of **grouped** and **classified** measurements
  - **Wind retrieval** for different observation types:
    - **Rayleigh-clear; Mie-cloudy**; **Rayleigh-cloudy; Mie-clear**
  - **Rayleigh corrections**:
    - **Temperature**, **pressure** sensitivity (**R**ayleigh-**B**rillouin **C**orrection) using *a priori (AUX_MET)* information
      - without this correction several m/s HLOS wind biases could occur
    - Account for Mie signal on Rayleigh channel using L1B scattering ratio

ECMWF

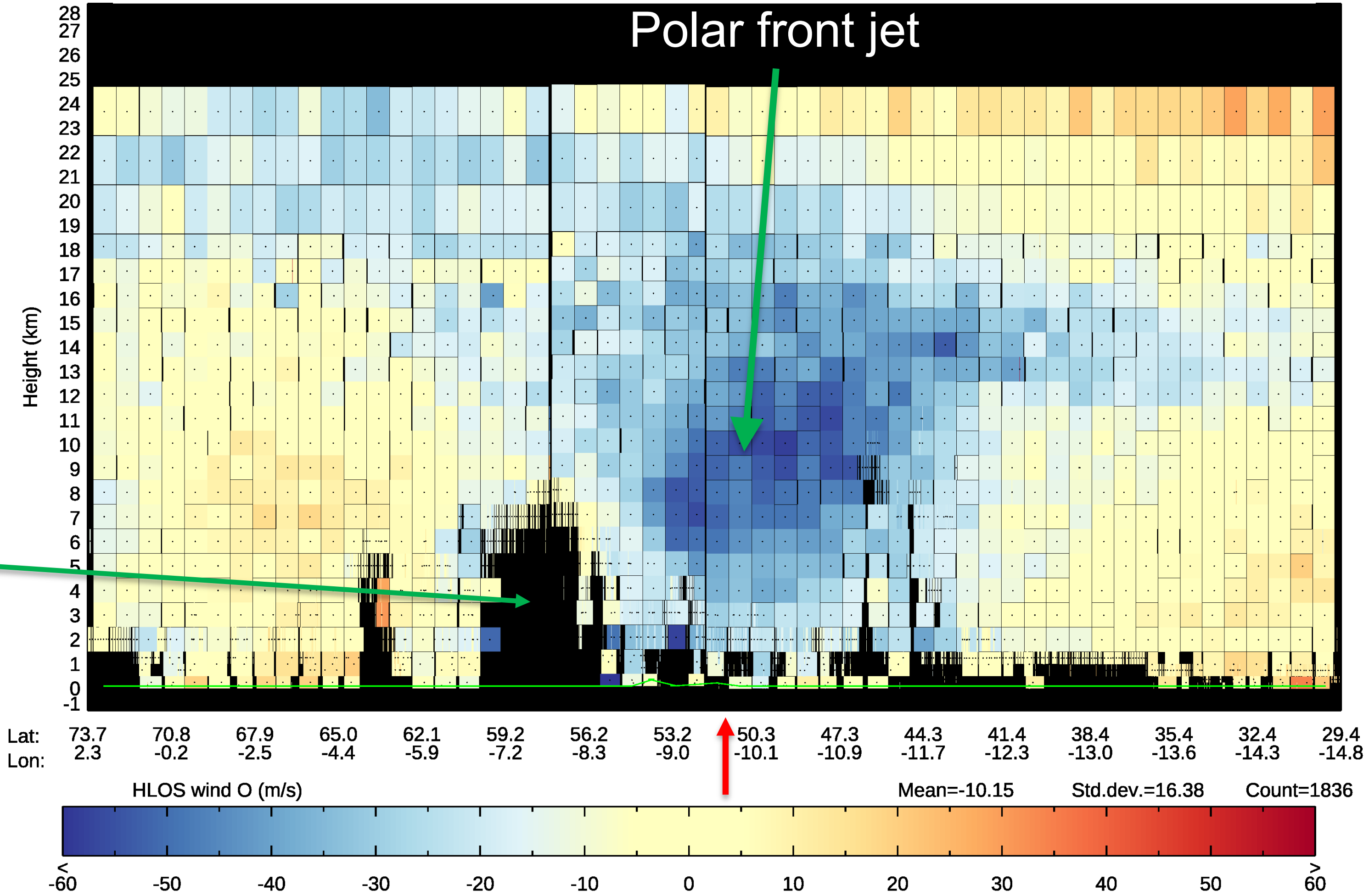
… continued

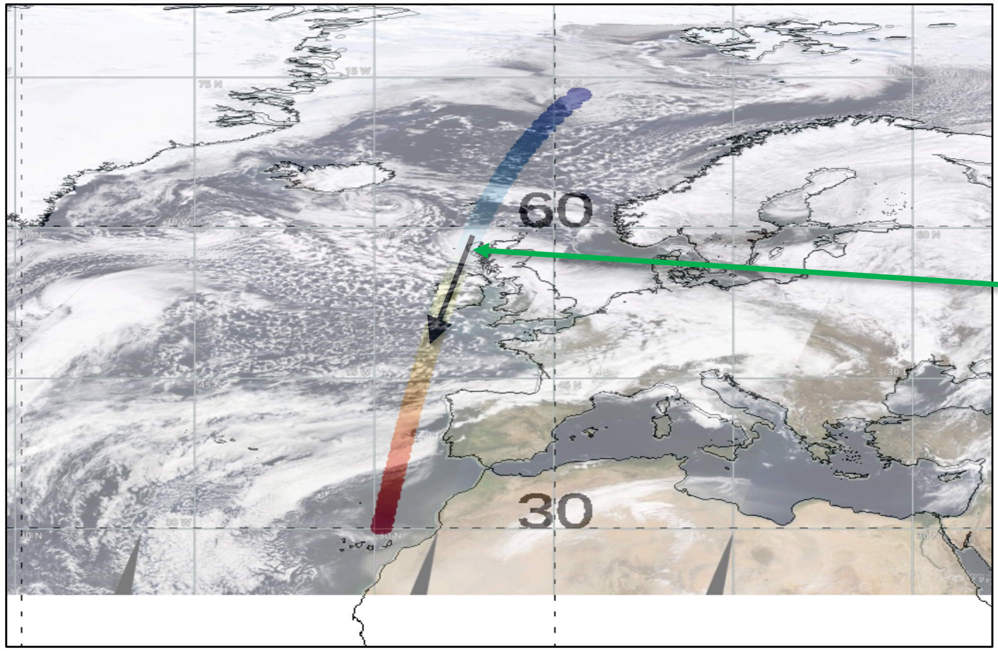
- Uncertainty estimates (dynamic instrument error estimate) and quality flags for each wind result
- Wind observations are essentially independent – however profile also provided pointing to observation index
- Most processing options controllable via settings file (flexible)
- Software freely available and highly portable: https://confluence.ecmwf.int/display/AEOL
- Additional tools in software package:
  - L2B EE to BUFR converter for NWP users
  - Various tools to write products to ASCII
- Aeolus L2B data can be browsed in the ADDF archive (https://aeolus-ds.eo.esa.int) and browsed and plotted by the VirES tool (https://aeolus.services/)

A very windy day in north-west Europe (10 March 2019)

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

What Aeolus observed (Rayleigh + Mie winds) near the low





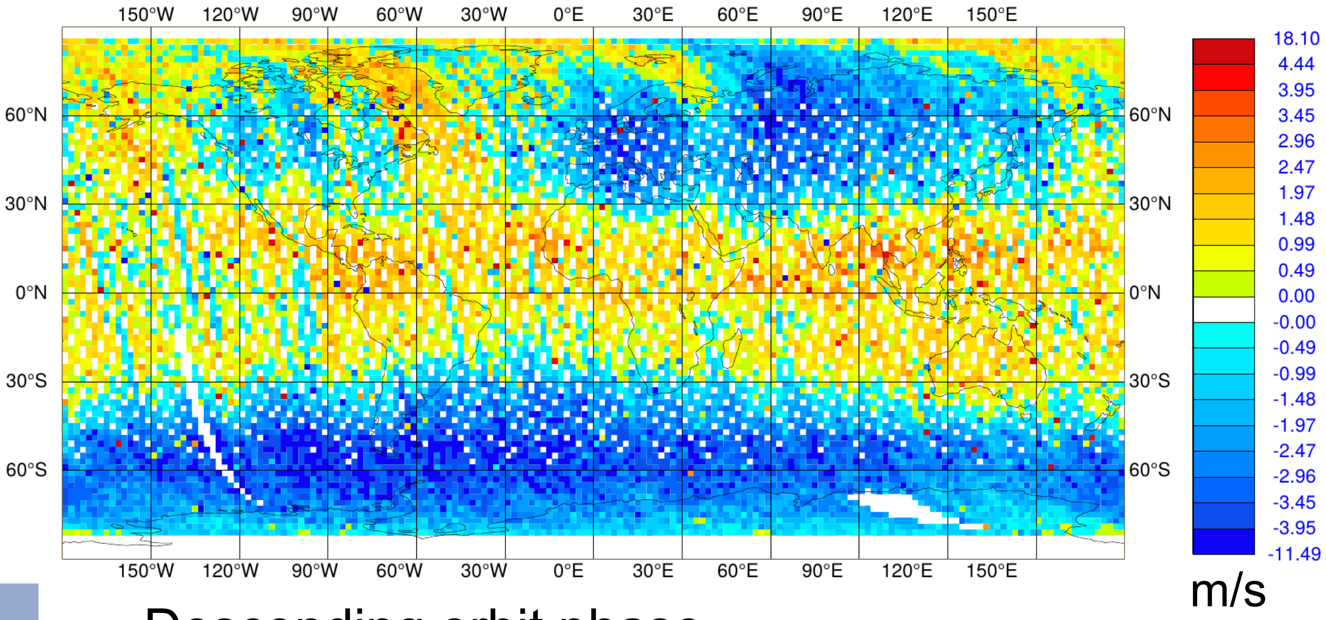
A breakthrough in 2019: explanation for dominant source of Rayleigh wind bias which varies on less than one orbit time-scales was found

- Investigations showed Rayleigh **wind bias**, which varies along the orbit, is strongly correlated with telescope **primary mirror temperatures variations**
- Temperatures vary due to varying Earthshine and the mirror’s thermal control
  - Temperature variations correlate with outgoing SW and LW radiation
- *Probable 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 is being implemented in next processor versions:
  - See references for more details:
  - https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.4142
  - https://amt.copernicus.org/articles/14/7167/2021/amt-14-7167-2021-discussion.html

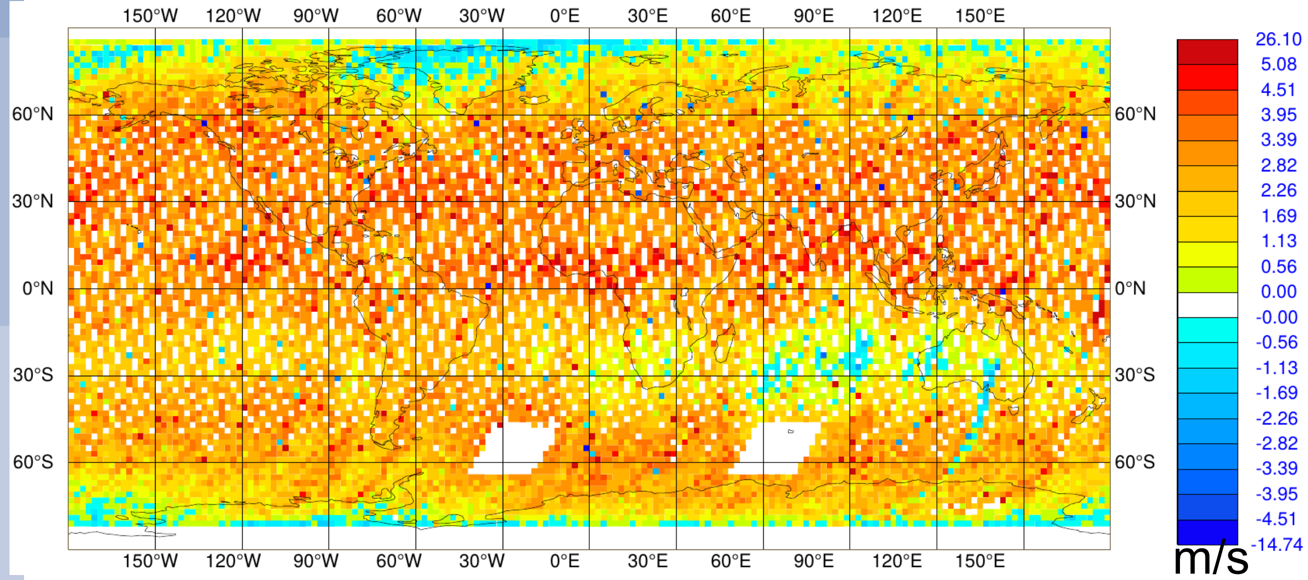
Rayleigh has large biases which vary with geolocation

Ascending orbit phase

e.g. 6/8/2019 to 7/9/2019

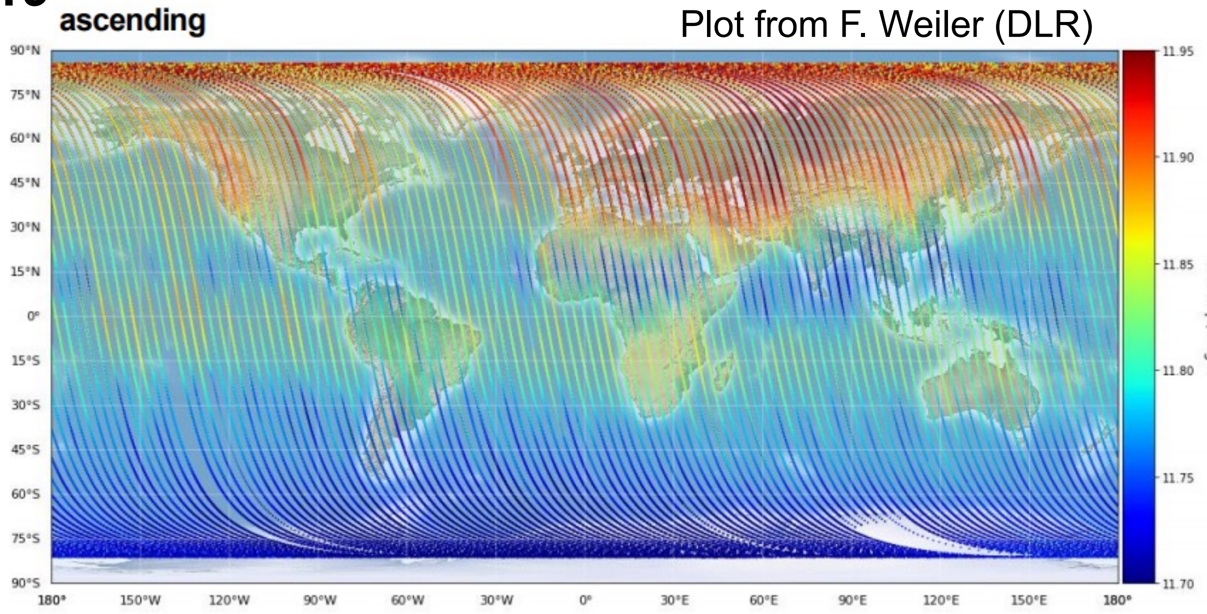


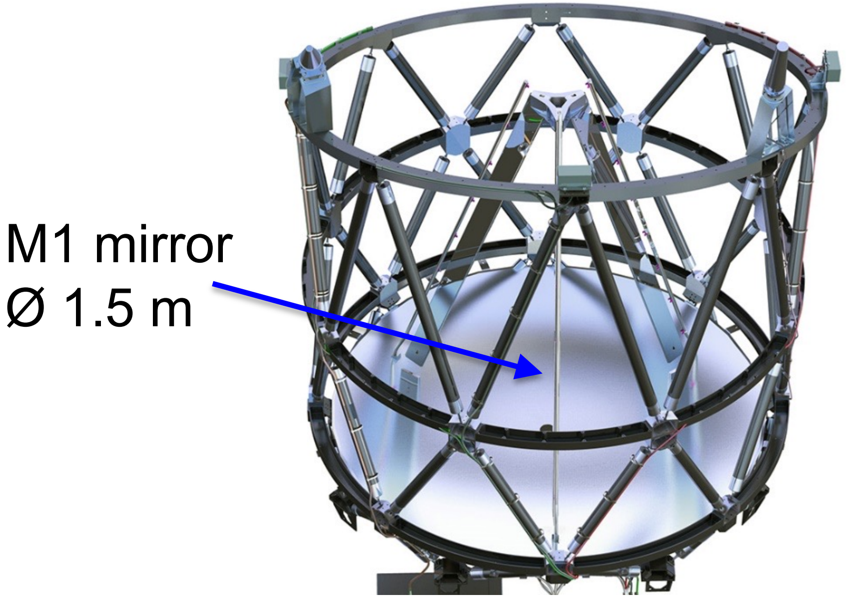
Descending orbit phase



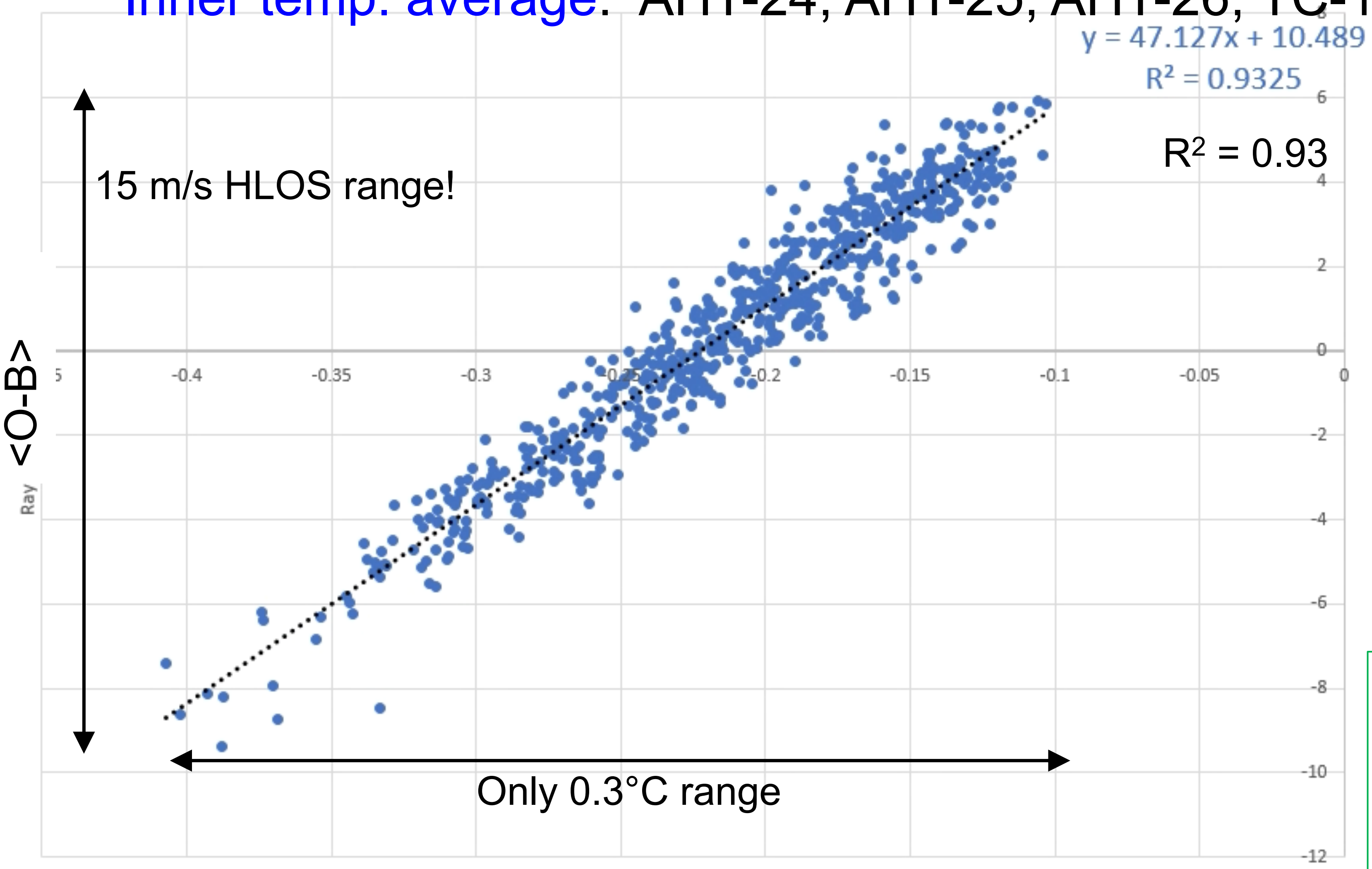
Average M1 telescope mirror temperature

Plot from F. Weiler (DLR)

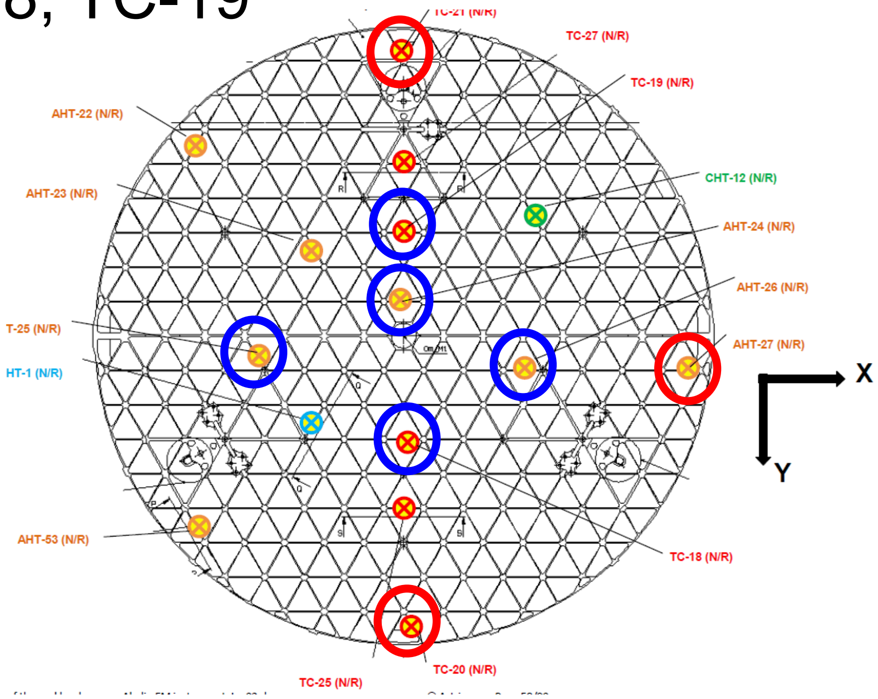




Regression of <O-B> versus M1 temperature function
Best results on 8/8/19 obtained with:
Outer temp. average: AHT-27, TC-20, TC-21
Inner temp. average: AHT-24, AHT-25, AHT-26, TC-18, TC-19

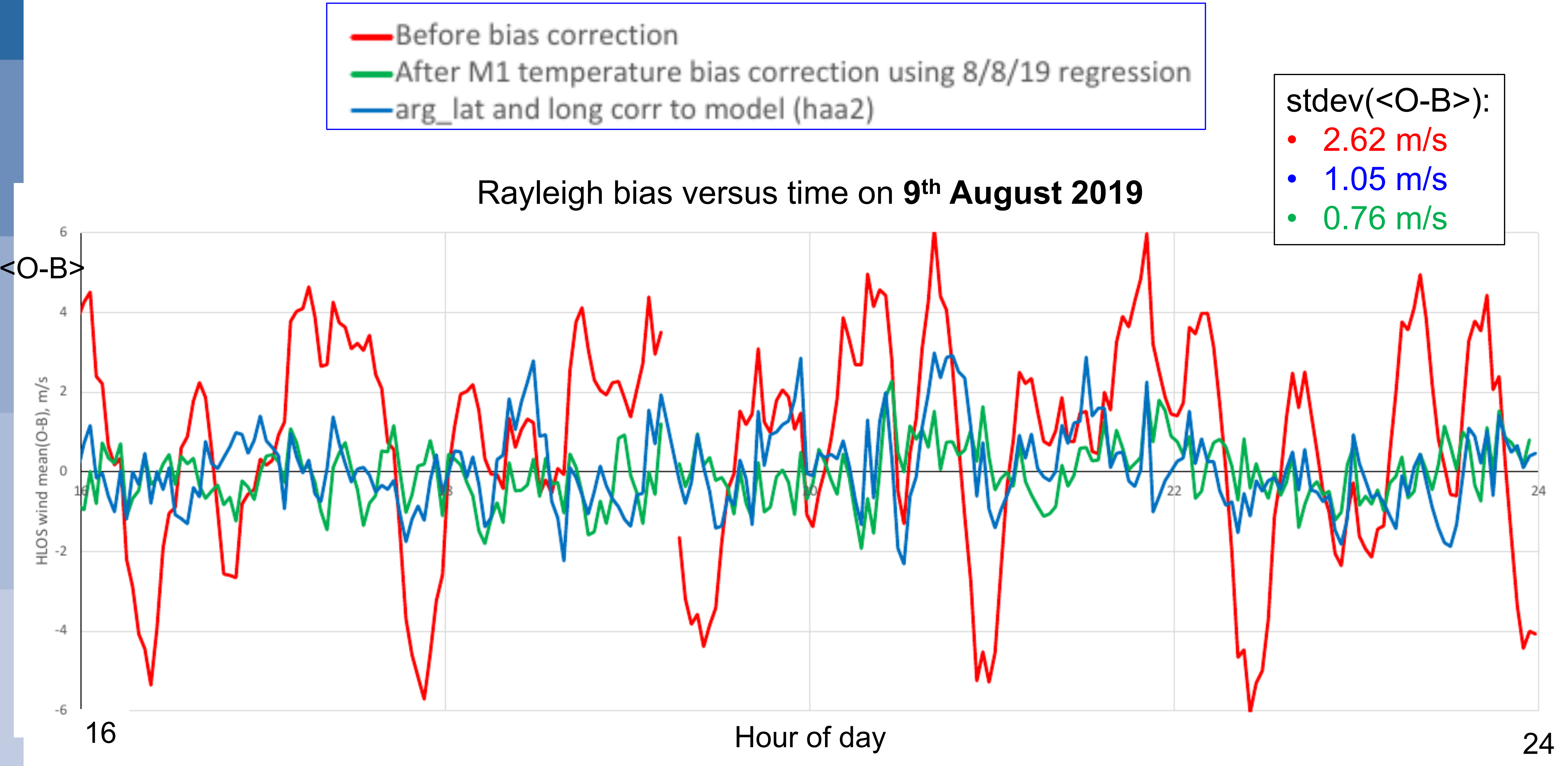


***Outer** minus **inner** M1 temperature function (°C)*



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

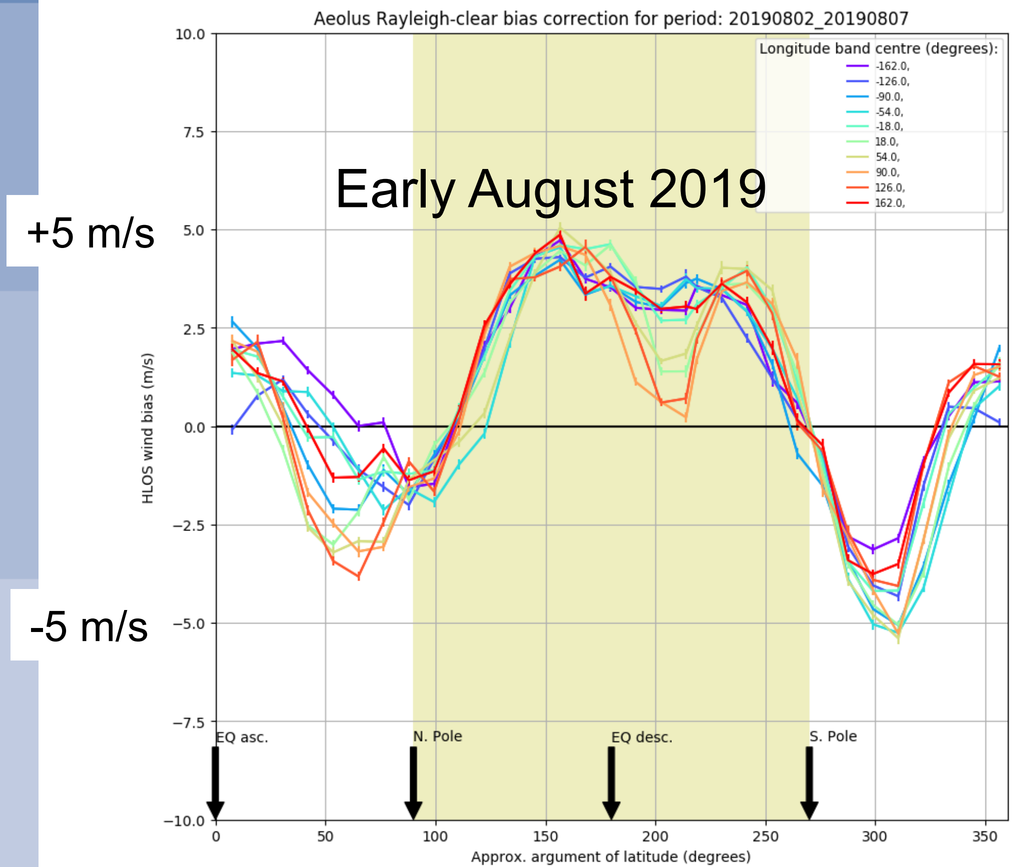
Example of bias correction



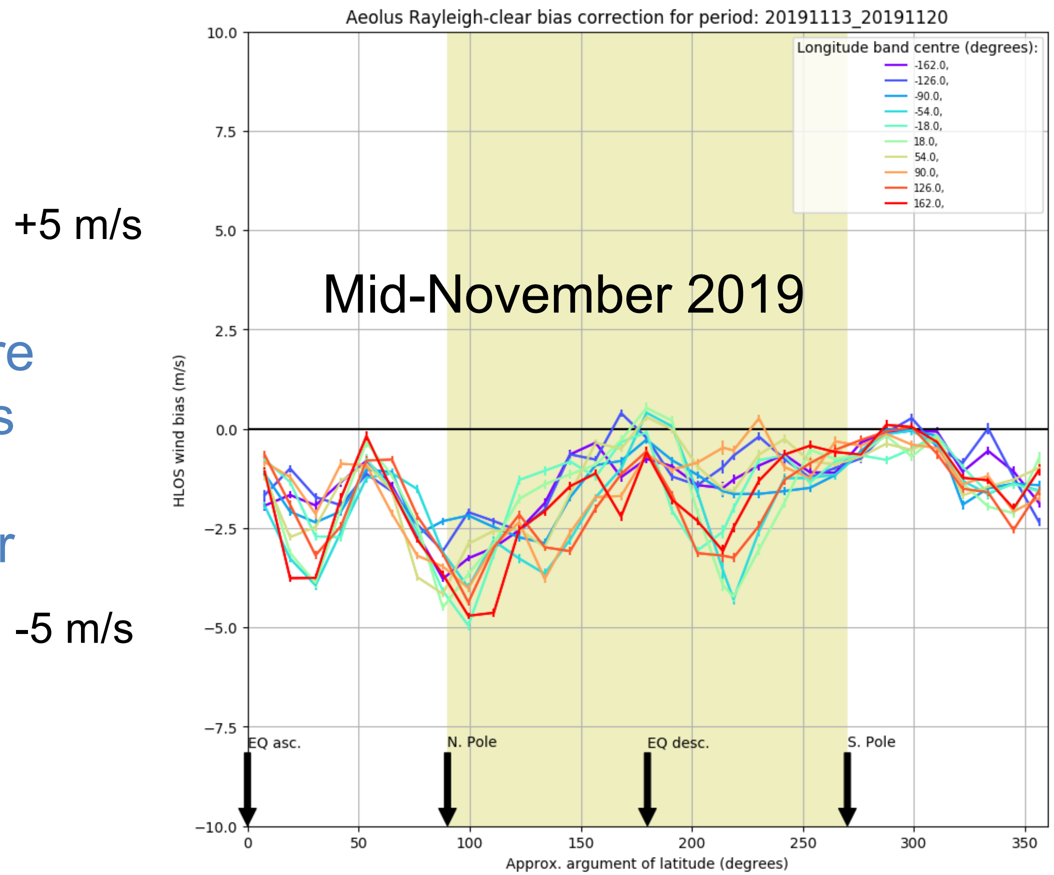
Bias correction to the ECMWF model

- Implemented bias correction scheme: *<O-B>* vs. *"orbit's argument of latitude" and longitude*
- Updates to bias correction look-up table done typically done every few days in experiments
- Mie biases very stable and do not require the longitude dimension

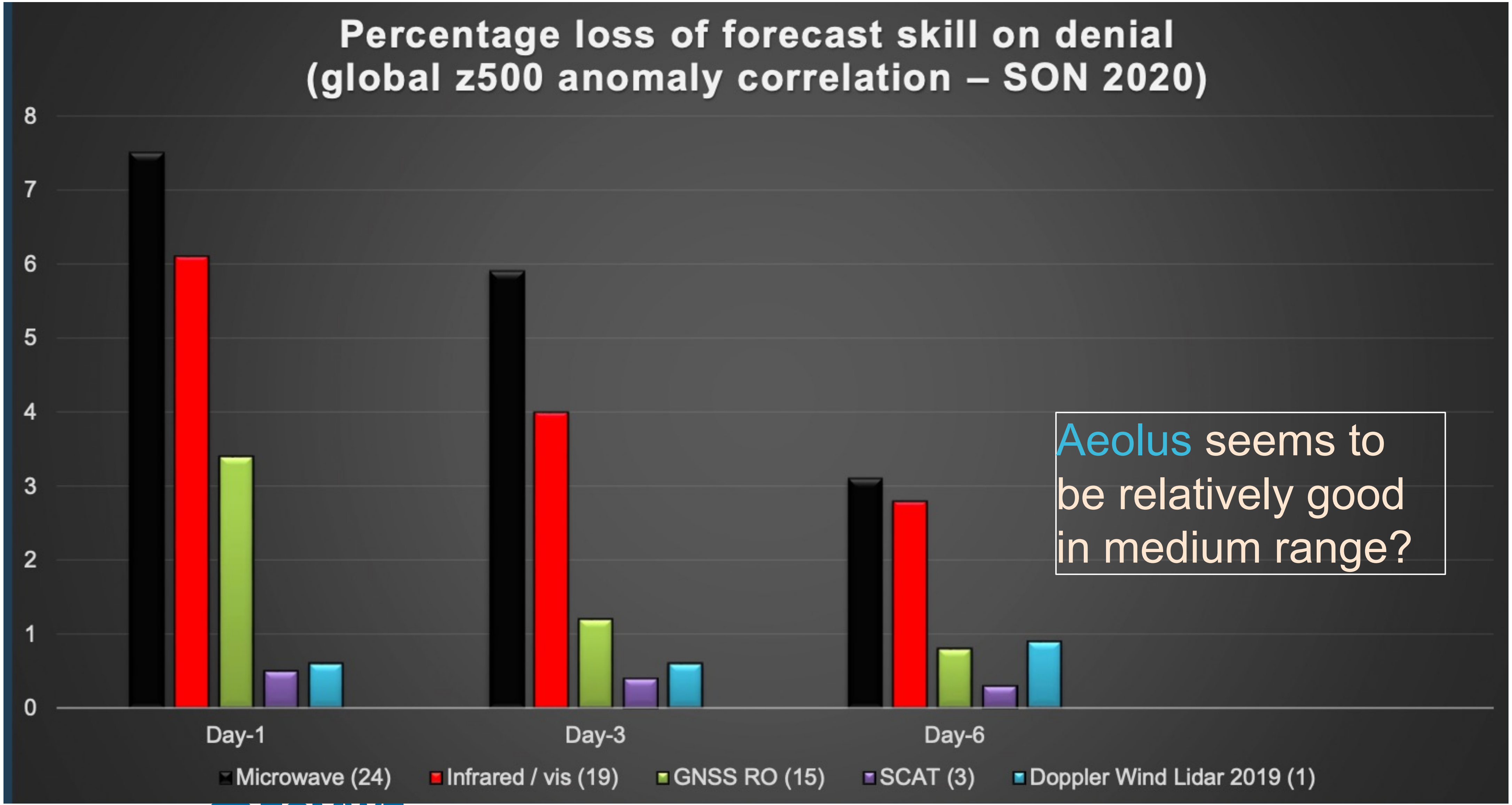
Example of how **Rayleigh** biases varied during the FM-B period



M1 temperature induced biases were larger in boreal summer



Aeolus does well for one instrument compared to existing multi-instrument satellite systems



ECMWF

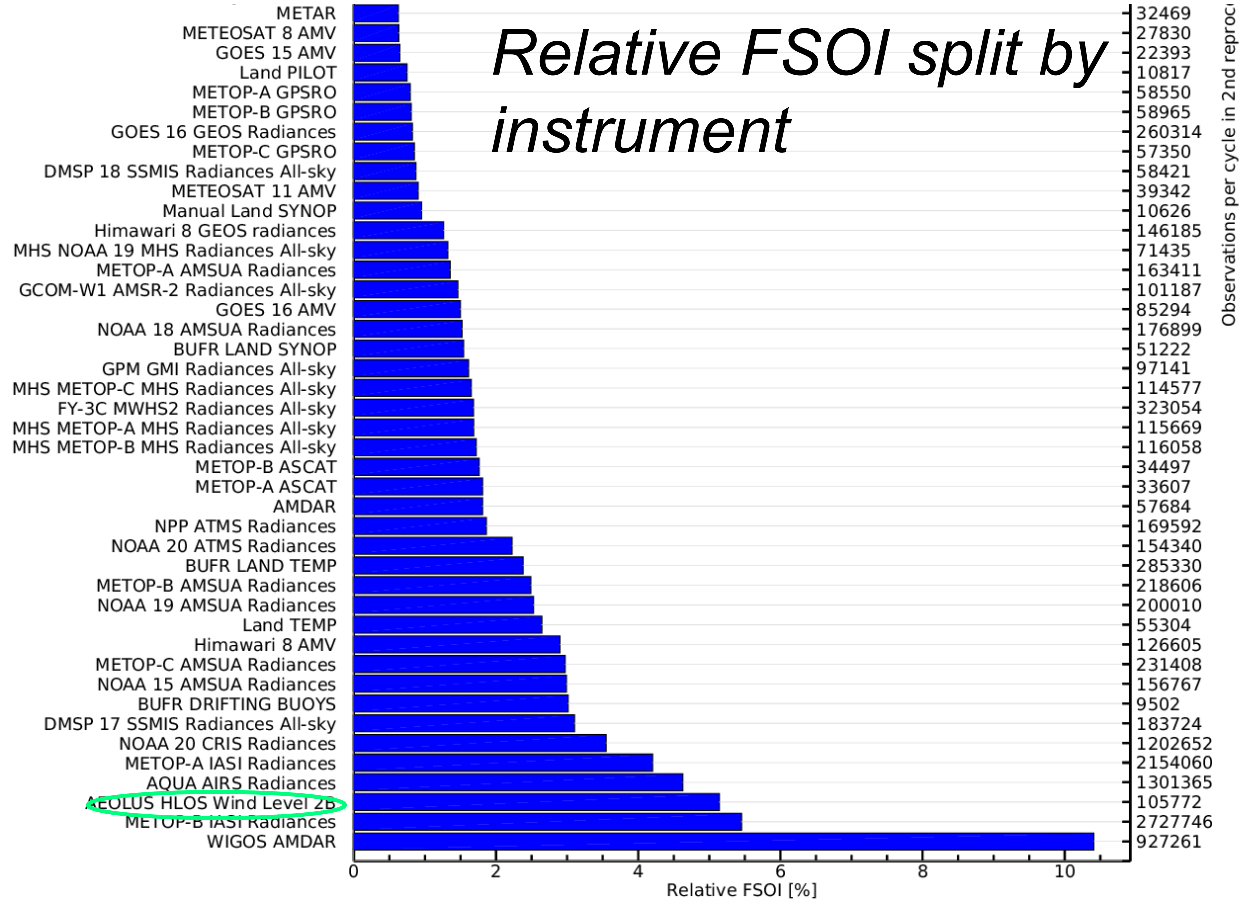
As shown by Tony on first day!

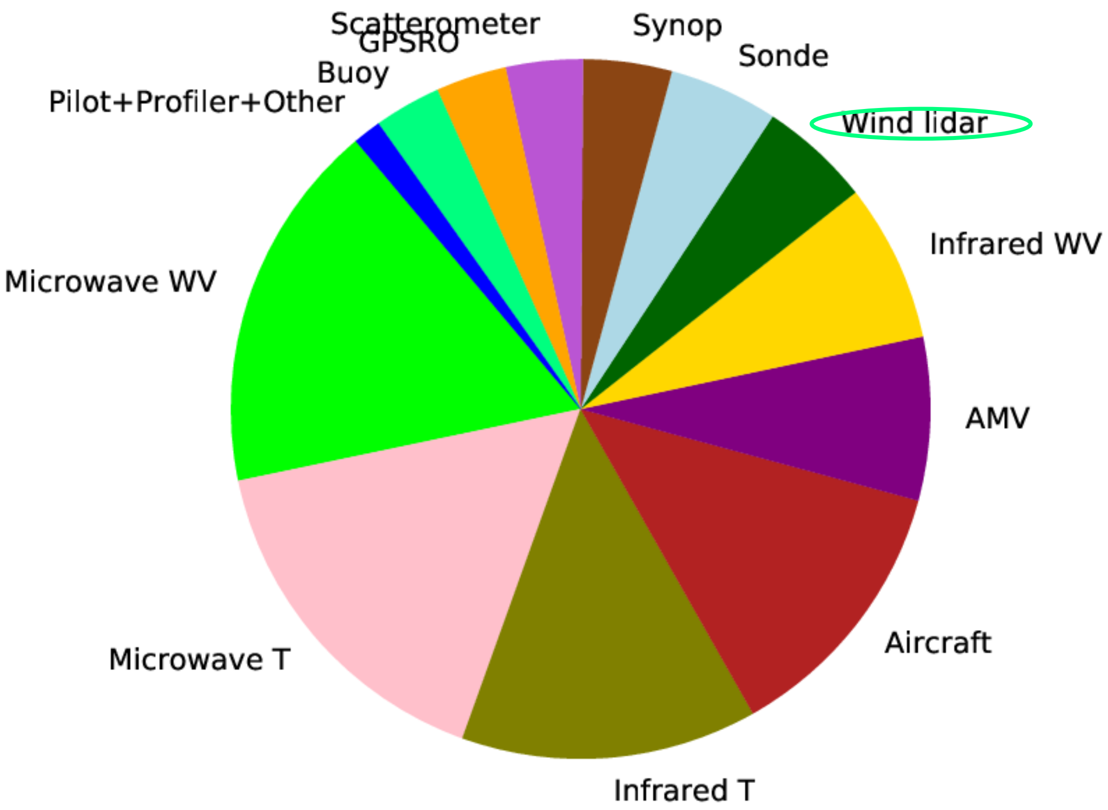
Summary of Aeolus NWP impact at ECMWF

- Aeolus provides a **strong impact** for one satellite instrument
  - Positive impact in most areas and ranges for wind, temperature and humidity
  - Largest impact in tropical and polar UTLS; into medium range

- Shows **importance of *additional* wind** observations in NWP – wind is still not a well-observed variable

Relative FSOI with 2nd reprocessed dataset; 3-29 July 2019 (*when Aeolus had its smallest random errors*)





- Aeolus has good impact for **one satellite instrument**
  - When have reasonable Rayleigh-clear random errors

- Wind lidar = Aeolus = 5.1%
- Larger impact than radiosondes for this period