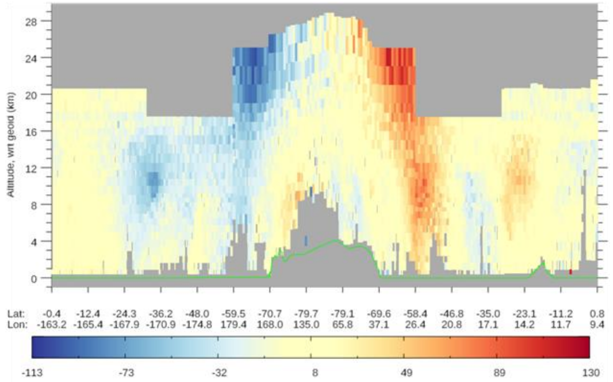
Error modelling and bias estimation for Aeolus winds

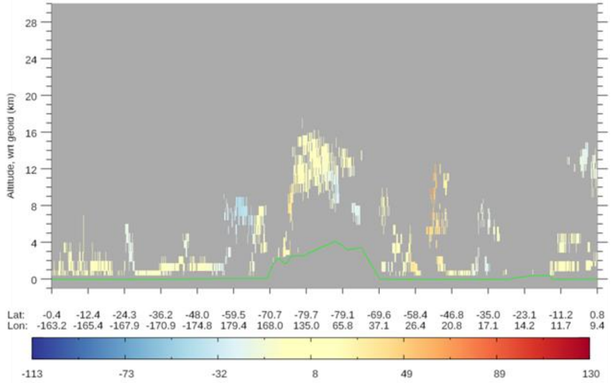
ECMWF/EUMETSAT NWP SAF Workshop on the treatment of random and systematic errors in satellite data assimilation for NWP

by **Michael Rennie (ECMWF)**
Acknowledgments: Isaksen L, Weiler F, Prithiviraj R, de Kloe J , Marseille G-J, Reitebuch O, Kanitz T, Bell B and Aeolus DISC team

European Space Agency



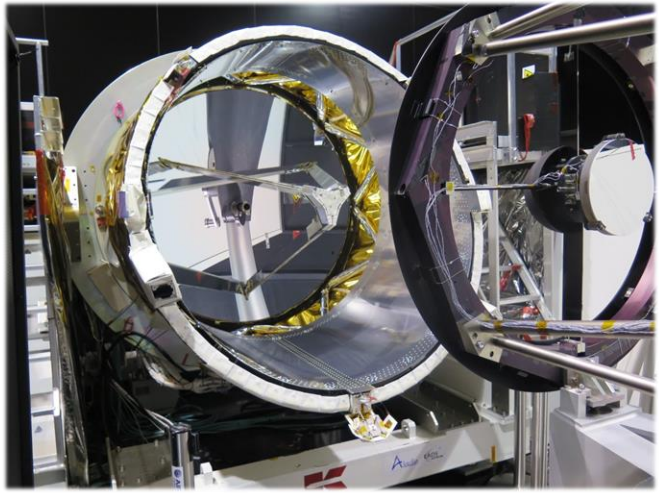
(a) L2B Rayleigh-clear HLOS winds



(b) L2B Mie-cloudy HLOS winds

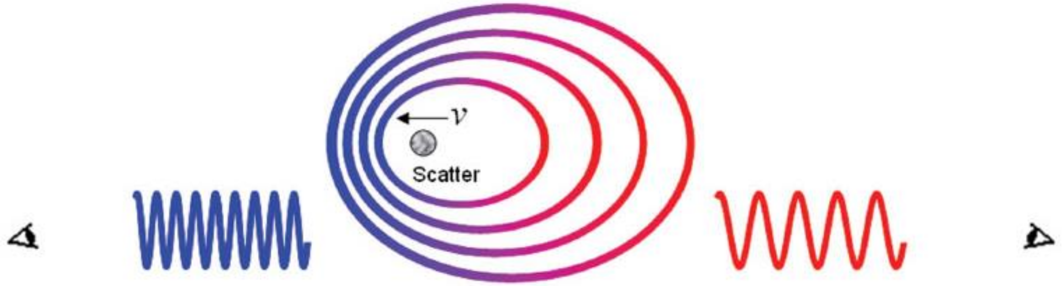
What is Aeolus?

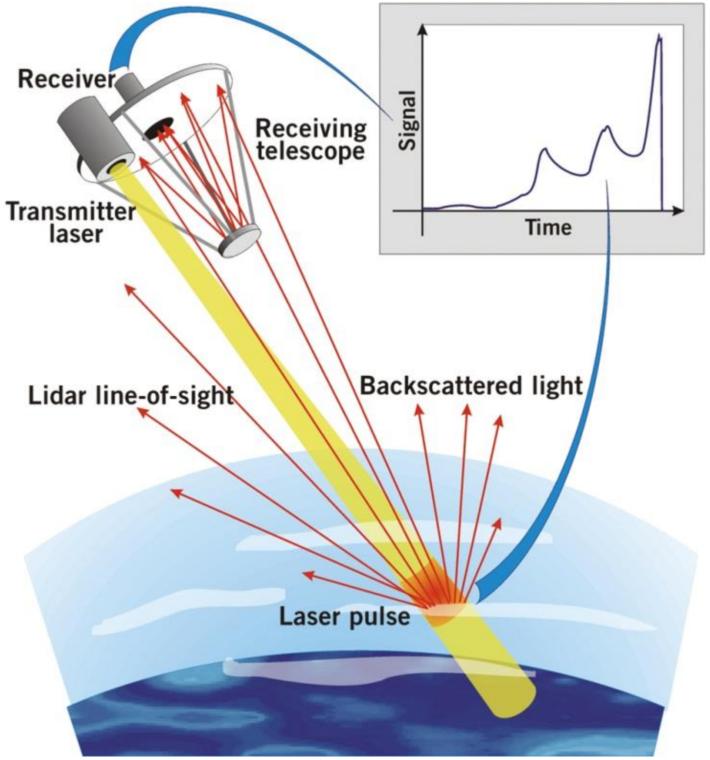
- Earth observation satellite. 5th Satellite of ESA’s Living Planet Programme (an Earth Explorer) – a technology demonstration
- Launched on 22 August 2018, after a decade delay
- **Scientific payload:** a Doppler wind lidar measuring profiles of line-of-sight winds
- Main goal is to improve weather forecasts and improve the understanding of the atmospheric dynamics
- Aeolus fills a gap in the global observing system
- Operationally assimilated at ECMWF since 9 January 2020



Doppler wind lidar

- Measures Doppler frequency shift of backscattered laser light

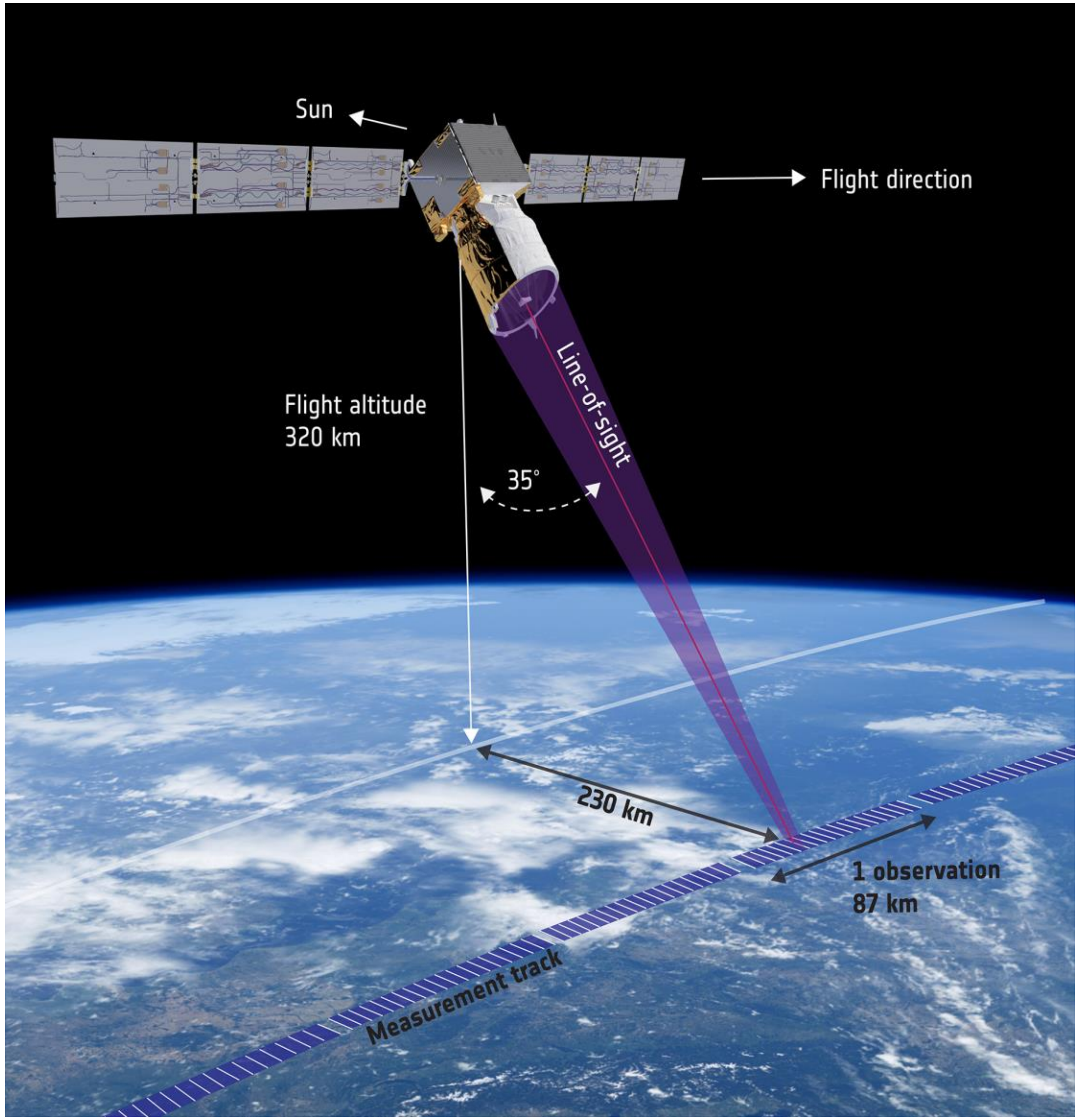




  - Doppler shift, $\Delta f = 2 f_0 v_{LOS} / c$

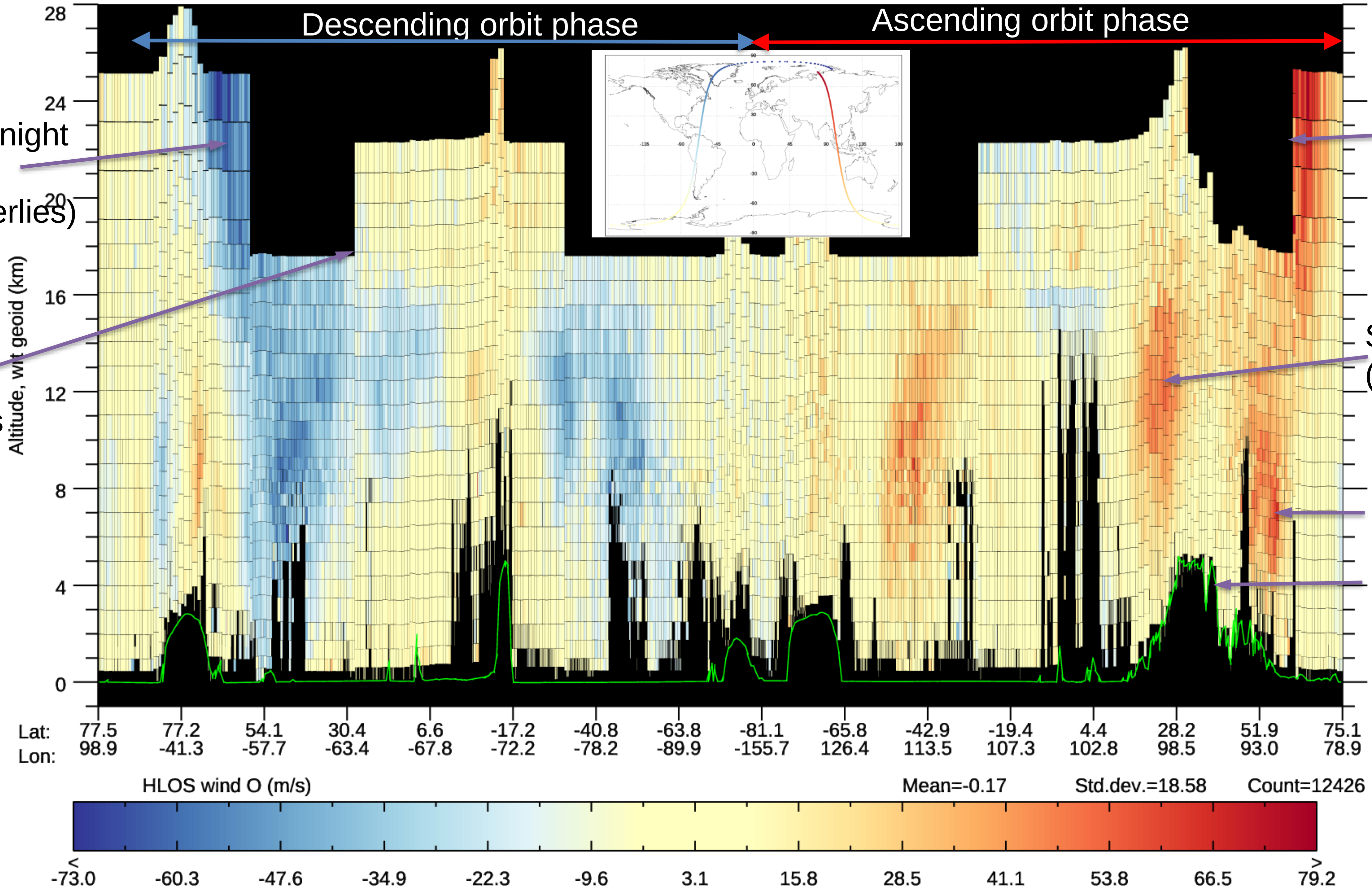
  - <u>Scattering from:</u>
    - Air molecules (clear air)
    - Particles (aerosol/cloud)
    - Ground
  - Line-of-sight (LOS) wind = average speed of movement of molecules/particle in volume of air along the LOS

Aeolus measurement principle



- Direct detection UV (355 nm) Doppler wind lidar with 50.5 Hz pulse repetition frequency, operating in continuous mode
- 2 channels:
  - Mie receiver to determine winds from cloud and aerosol backscatter
  - Rayleigh receiver to determine winds from molecular (clear air) backscatter
- The line-of-sight (LOS) points 35° off-nadir to determine Doppler shift due to horizontal wind component (and vertical)
- LOS is yaw-steered to be perpendicular to satellite-ground relative velocity

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



Polar-night jet (westerlies)

Varying range-bin settings

Polar-night jet (westerlies)

Subtropical jet (westerlies)

Polar front jet (westerlies)

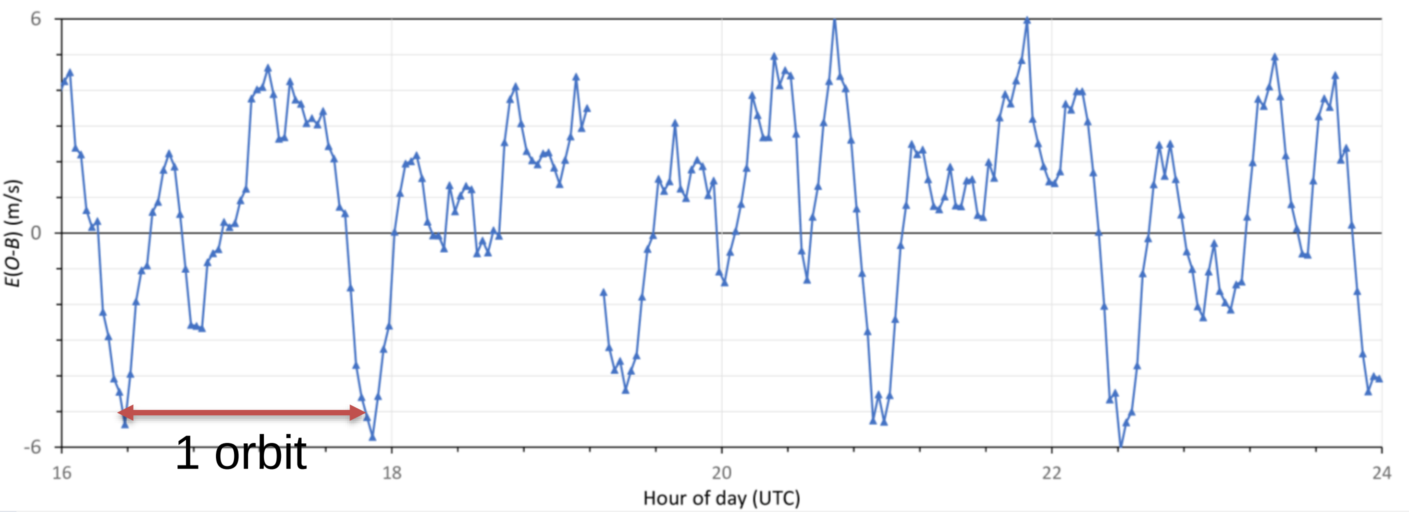
Mountains

Aeolus HLOS winds are positive if wind blowing away from satellite

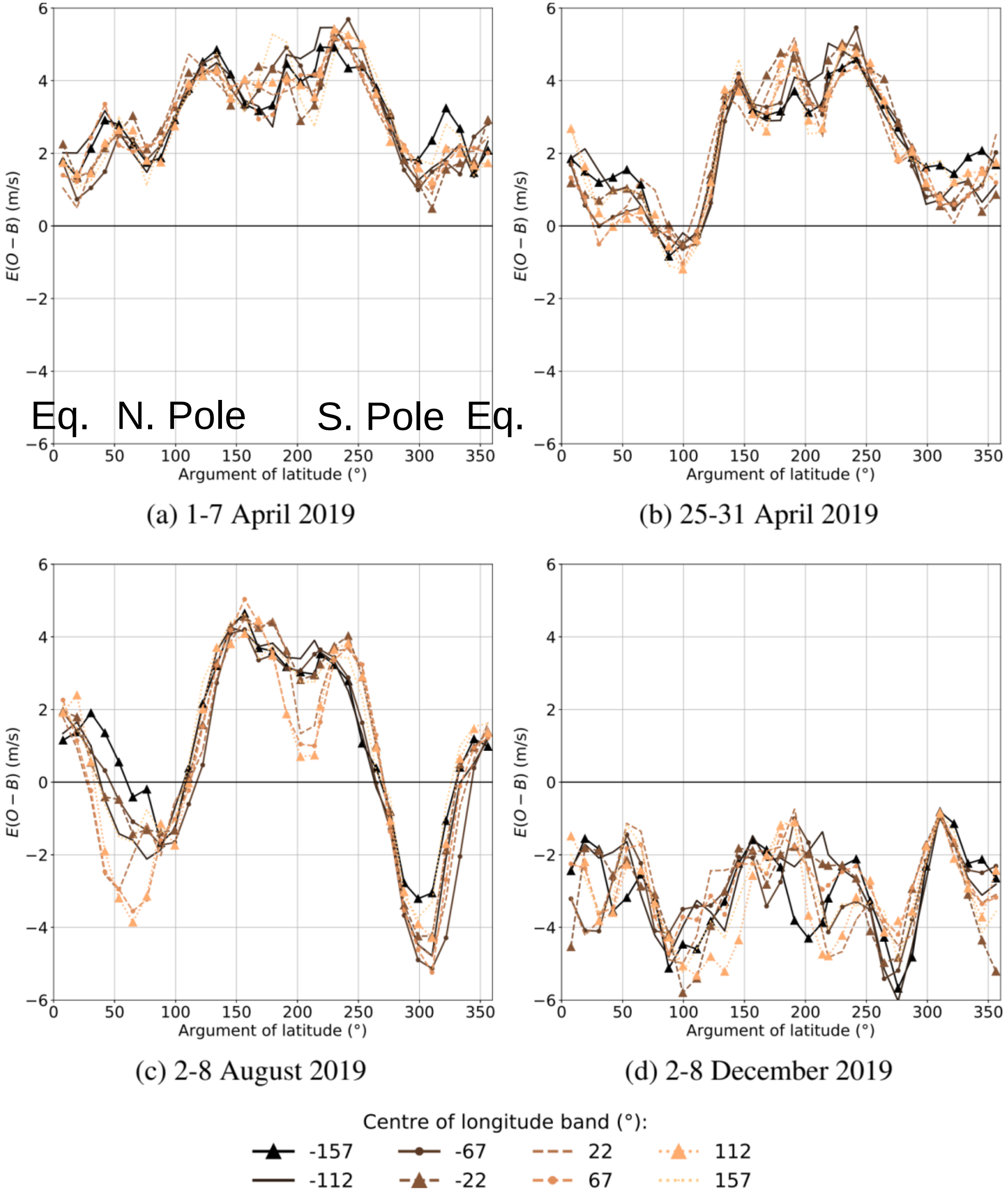
Topic 1: An important contribution to Aeolus Level-2B HLOS wind systematic errors and its correction in the ground processing chain

Aeolus Rayleigh-clear HLOS winds have large biases which vary along the orbit

Profile average bias (2 minute samples) vs time, 16-24 UTC on **9 August 2019**



Profile average bias (1 week) vs orbit phase angle



(a) 1-7 April 2019

(b) 25-31 April 2019

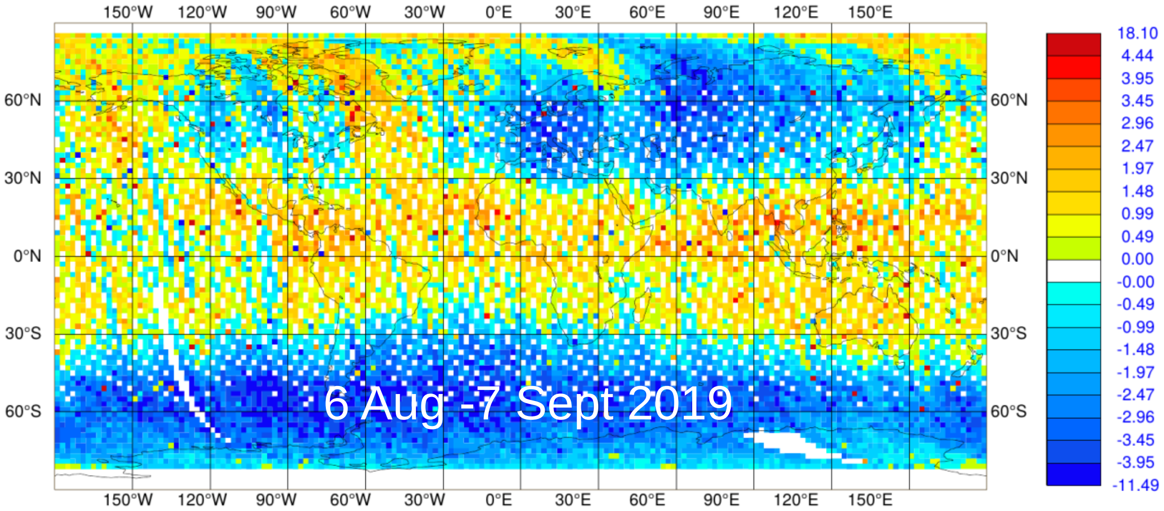
(c) 2-8 August 2019

(d) 2-8 December 2019

- Bias repeated (to some extent) with orbit phase
- Bias structure varies with the seasons
  - Large change at N. Pole during Spring (April 2019)
  - Larger variations with orbit phase in NH Summer, with ±6 m/s range
  - Smaller range in NH Winter
- Some longitudinal variation also

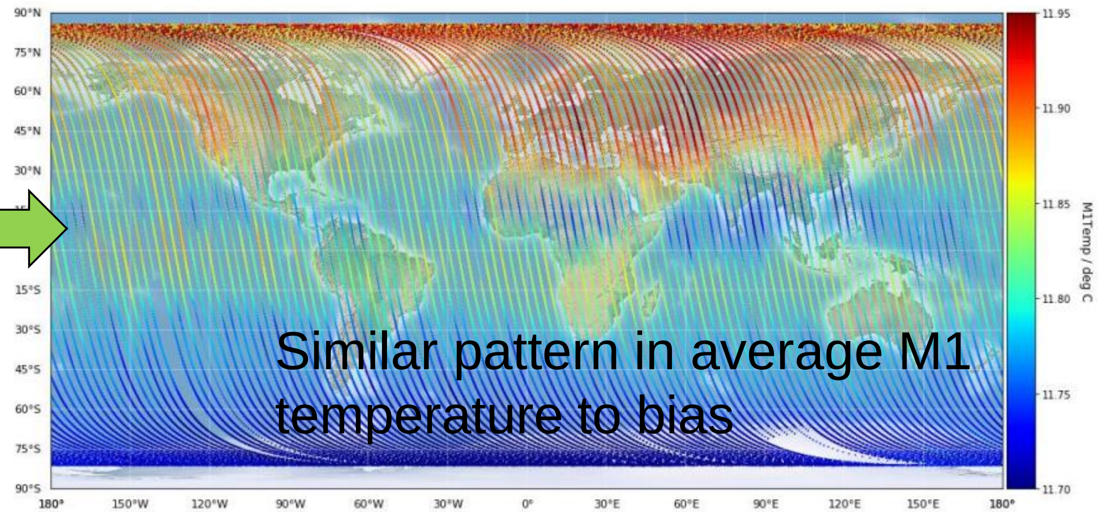
Noticed that Rayleigh-clear biases were somehow dependent on the temperature of the telescope primary mirror (M1)

Ascending orbit phase $E(O-B)$ m/s



6 Aug -7 Sept 2019

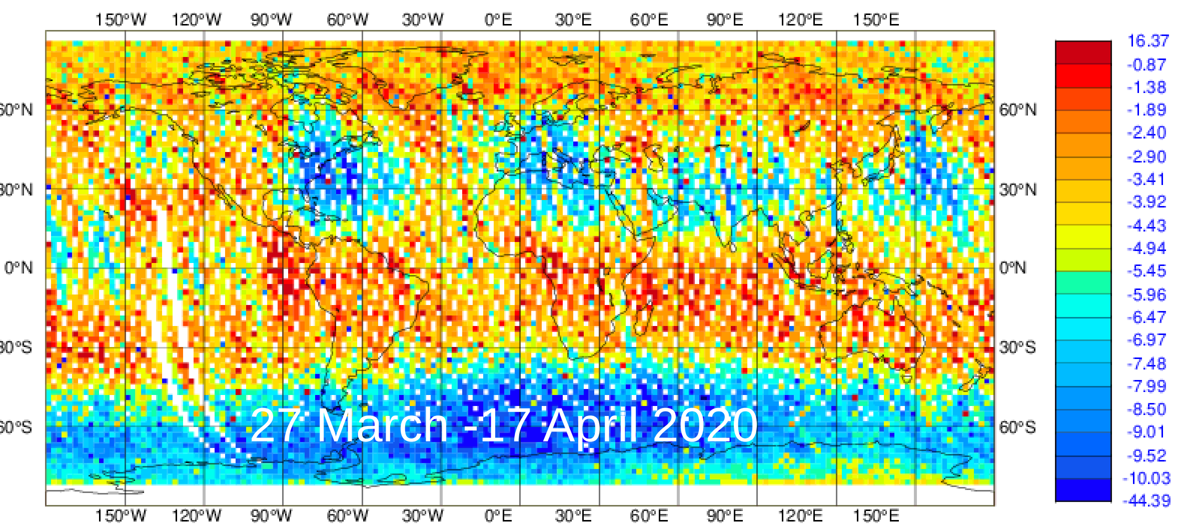
Average M1 mirror temperature



Similar pattern in average M1 temperature to bias

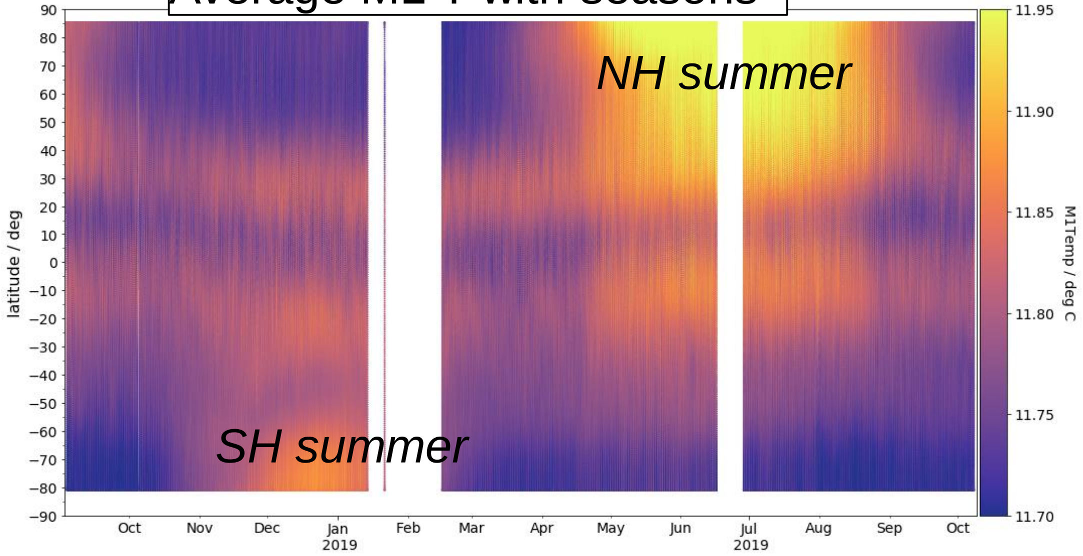
Plots by F. Weiler (DLR)

Variations in bias with latitude and longitude



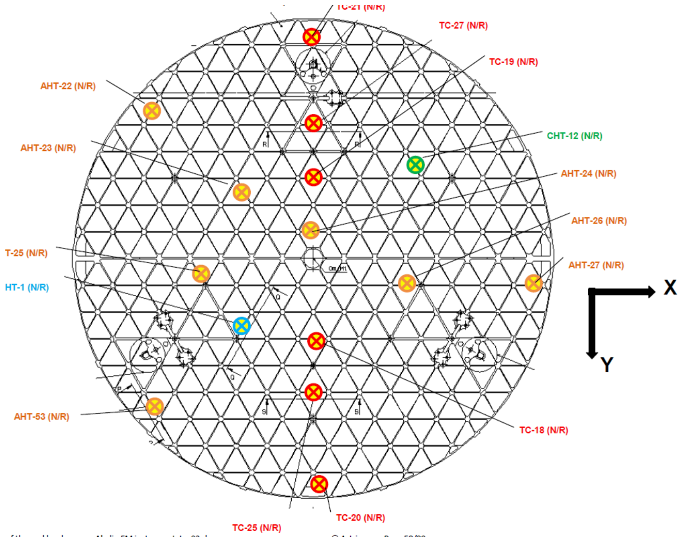
27 March -17 April 2020

Average M1 T with seasons

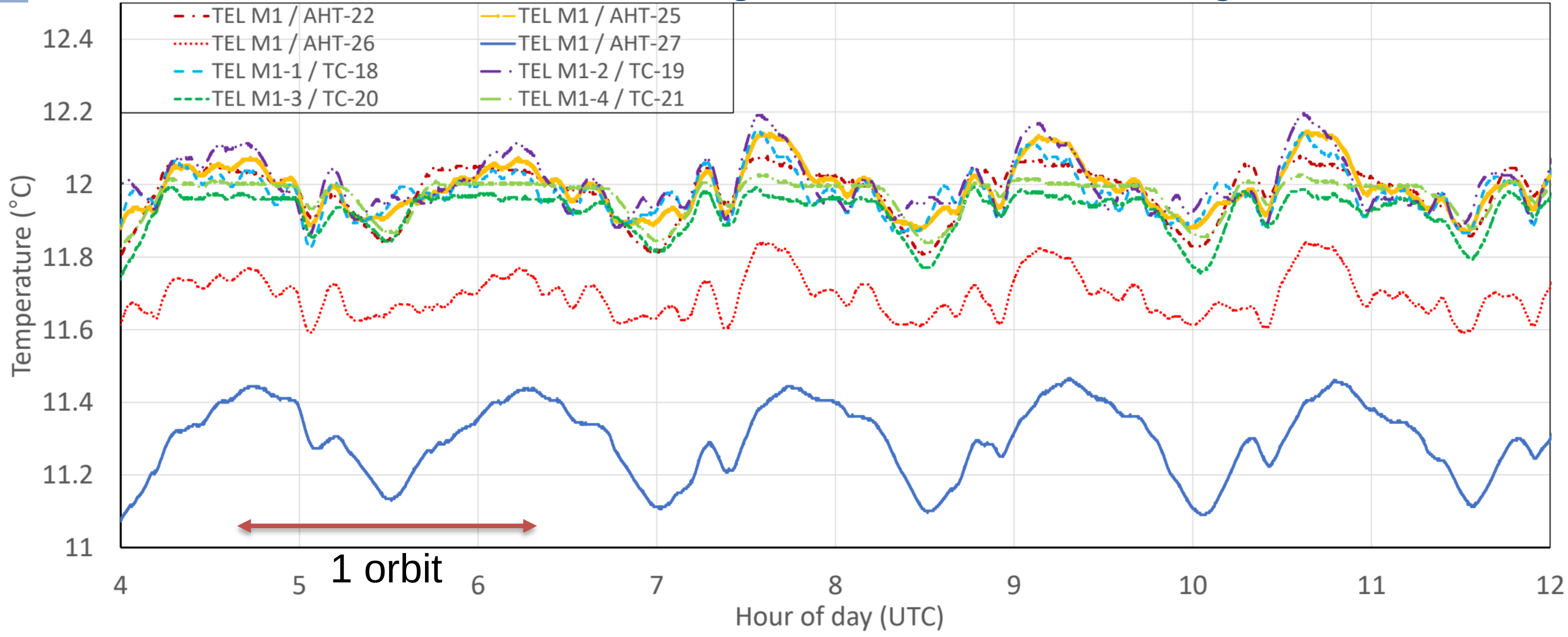


M1 mirror thermistor readings

- 15 thermistors distributed over the back of the mirror – available in satellite house-keeping data
- There are also heating panels on the back for thermal control



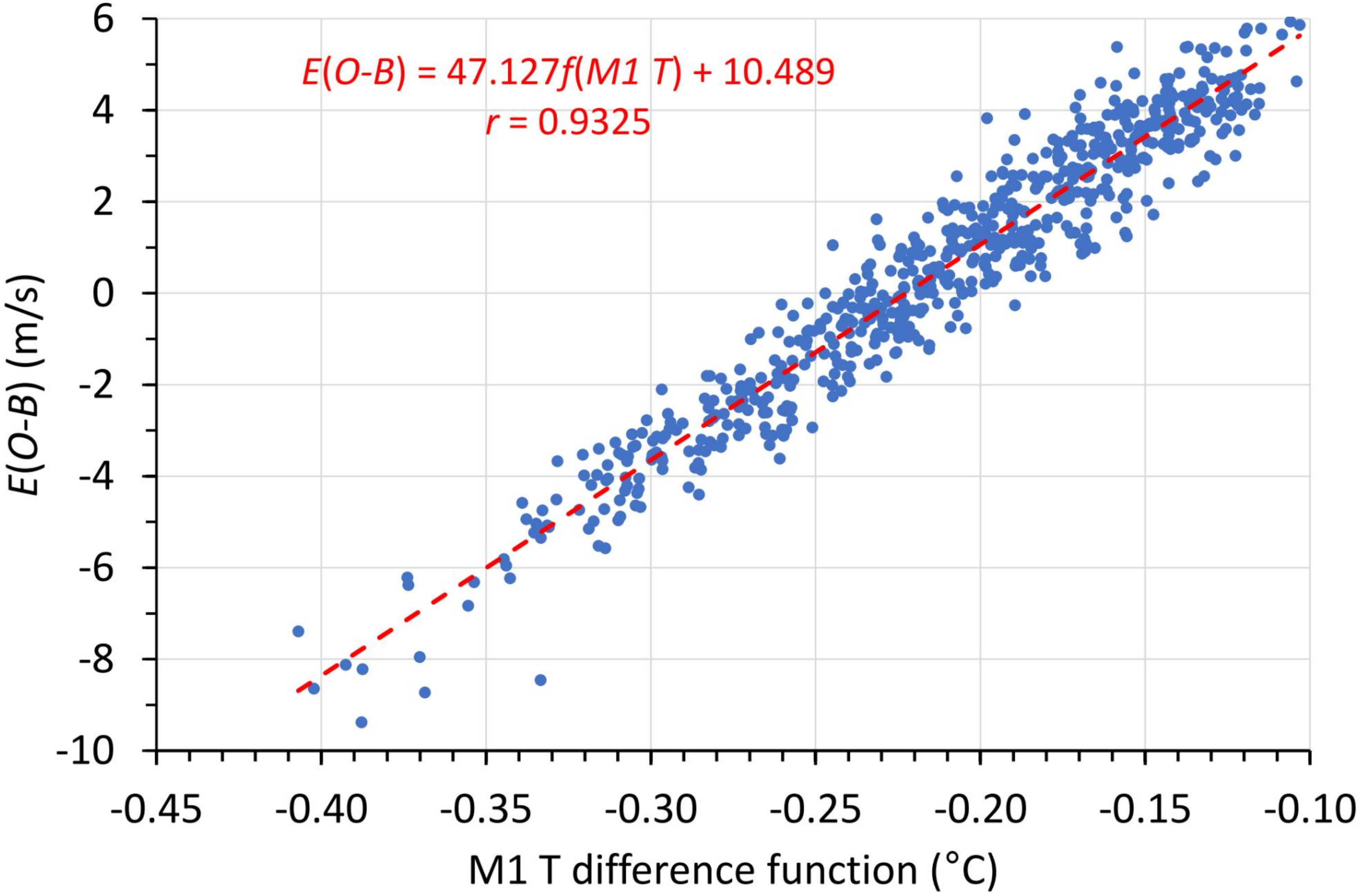
A selection of M1 thermistor readings for five orbits on 8 August 2019



- Orbital periodicity to the M1 temperature variations
- Due to variations in earthshine and mirror thermal control in response

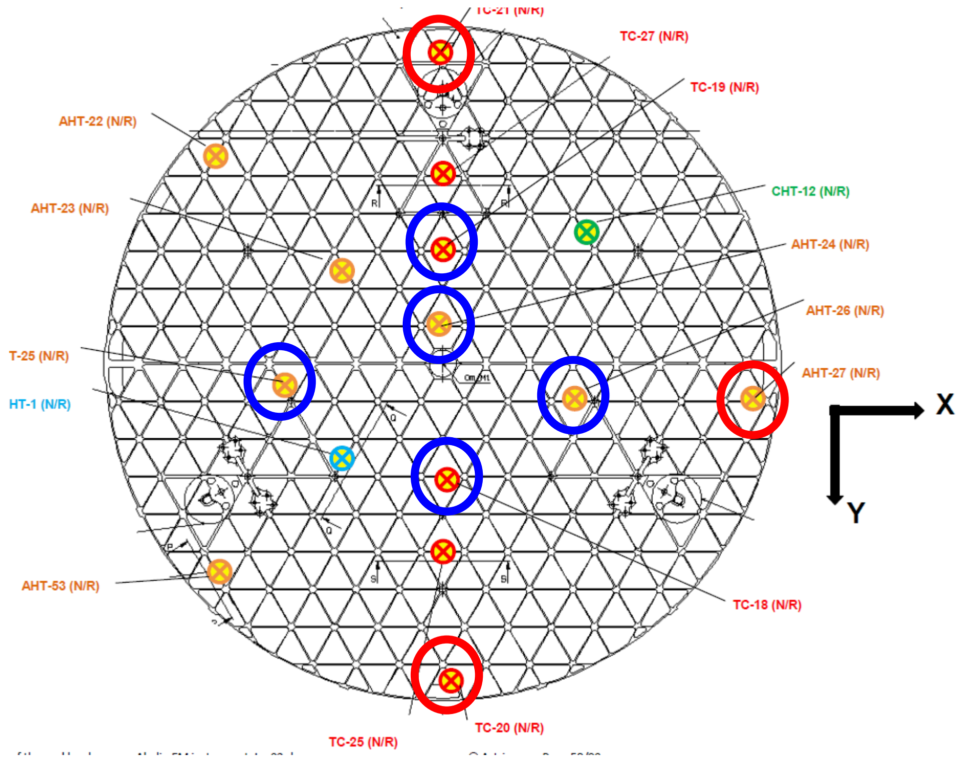
A breakthrough:

Rayleigh $E(O-B)$ versus M1 temperature gradient function (mean outer minus mean inner temperatures) **approximately linear**



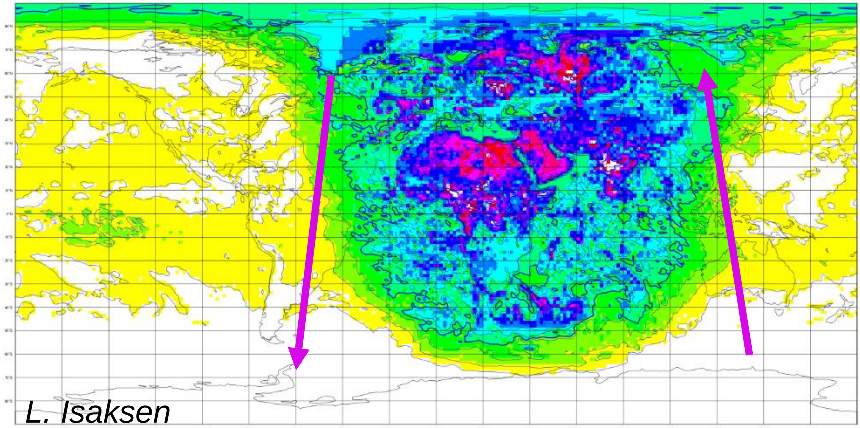
Outer temperatures

Inner temperatures



In Autumn 2019 the root cause for the Rayleigh wind bias was confirmed

- Comparing ECMWF O-B departures and satellite house-keeping data led to discovery that dominant source of sub-orbital Rayleigh wind bias **is linearly related to the telescope M1 mirror temperature gradients**
- M1 T varies with amount of earthshine (short and long-wave radiation) and the thermal control by heaters (behind mirror) which try to stabilise the temperature



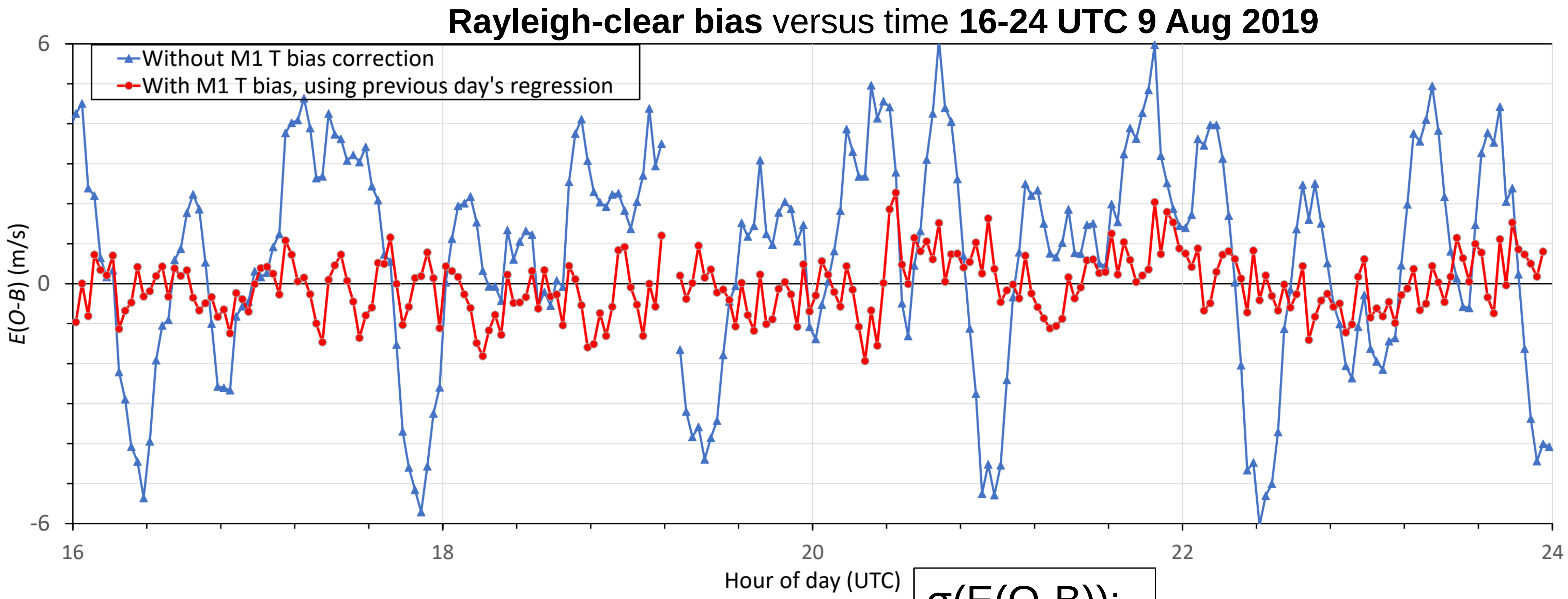
Reflected solar and thermal IR radiation from ECMWF model

Aeolus flies along the terminator

- ***Physical mechanism for the bias:*** temperature changes affect mirror shape and hence focus, causing changes in angular incidence of light upon the spectrometers
  - Spectrometer response is sensitive to frequency (Doppler shift) and **angle of incidence** (misinterpreted as frequency changes) – signal amplitude is also affected ~10%
  - Such biases were considered pre-launch, but with small magnitude and were expected to be corrected by a harmonic (with orbit phase) fit to ground return winds

With the linear relationship, we can perform a bias correction

- Use the linear regression on **day N** to correct L2B winds on **day N+1**



σ(E(O-B)):
- 2.62 m/s
- 0.76 m/s

Hence, an operational M1 T bias correction

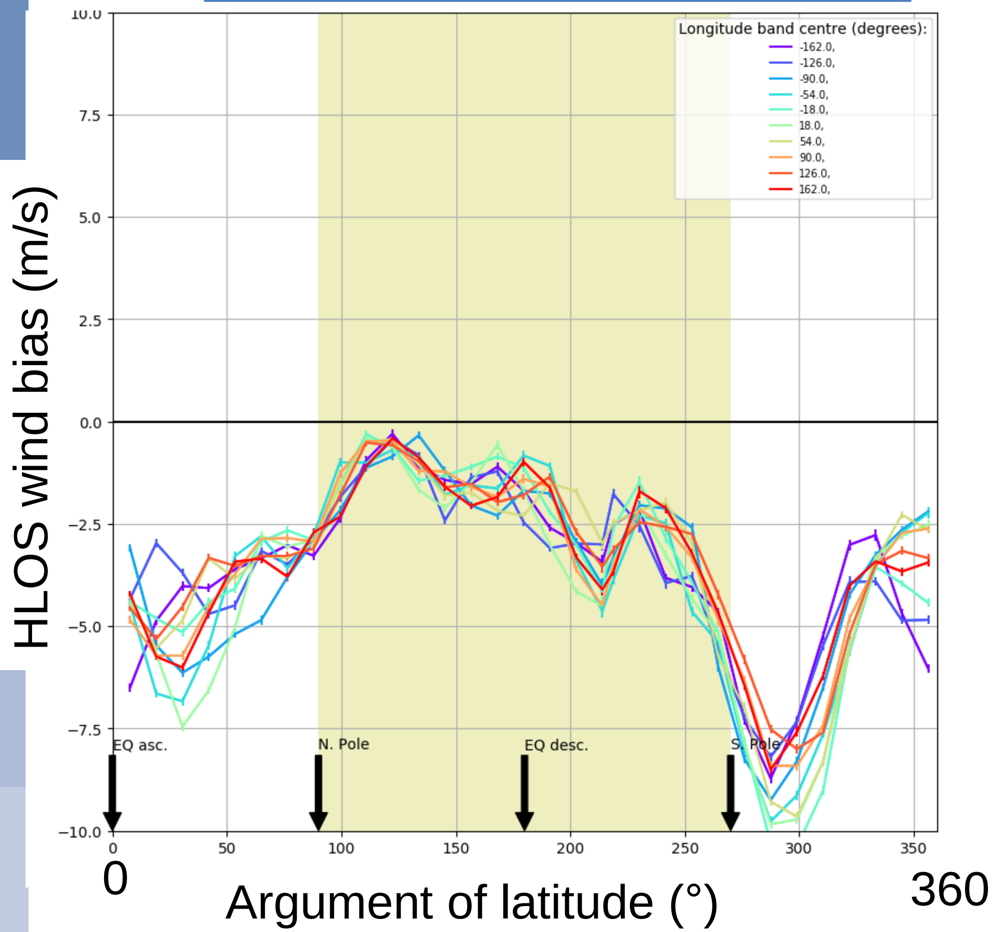
- **Multiple linear regression with all M1 thermistors** (T. Kanitz (ESA), F. Weiler (DLR)) was shown to perform better than fixed temperature function

$$Bias = \beta_0 + \beta_1 \cdot AHT_{22} + \cdots + \beta_{15} \cdot TC_{32} + \varepsilon$$

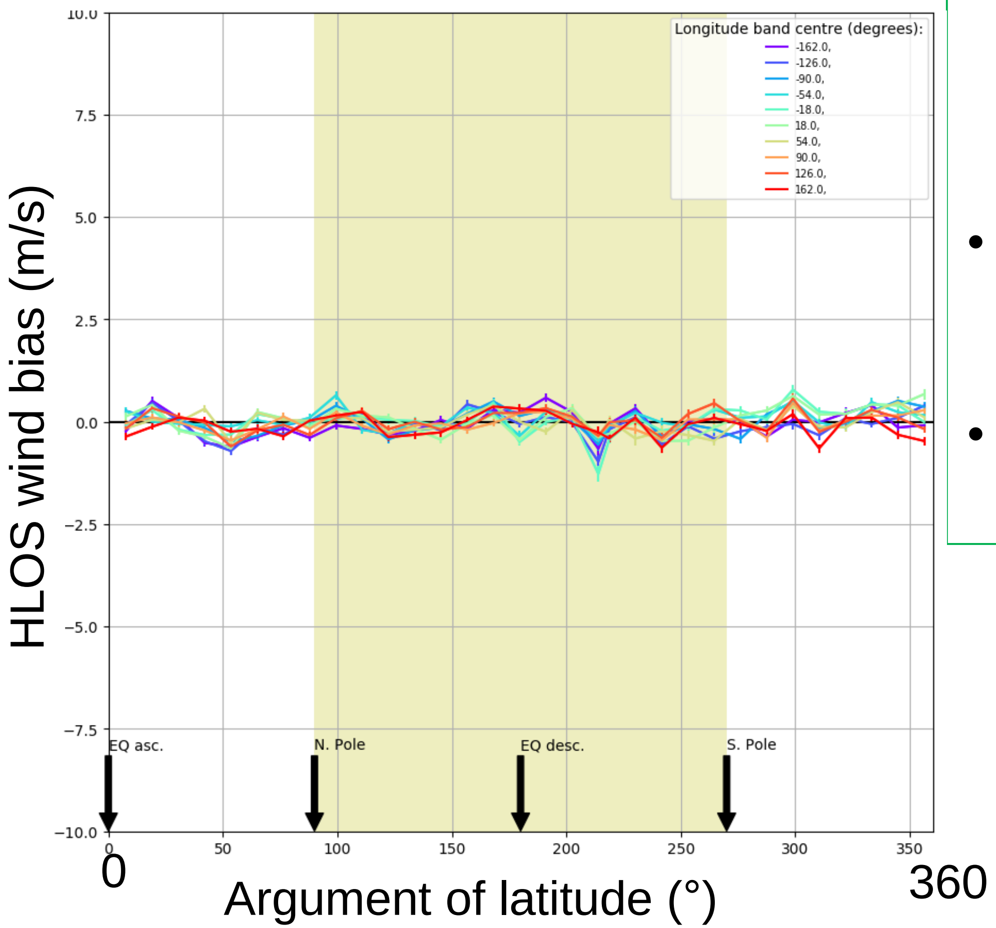
- Software to generate regression coefficients developed by F. Weiler, producing an auxiliary file that is applied in L2B processor, as the **M1 T bias correction**
  - Operational since 20 April 2020
  - Updated twice per day using past 24 hours' of ECMWF O-B departures
    - Regular updates required to remove drifting global offset bias (internal path issue)
- Correction via NWP model ***is not ideal***
  - However, global u-wind radiosonde *E(O-B)* < 0.3 m/s; so model biases must be relatively small in global average sense. We do a global, all day, all level fit
  - DWD and Météo-France confirm low biases after using the M1 T bias corrections
- **Ground return winds** can be used as reference (F. Weiler), instead of O-B departures
  - This works reasonably well, but relatively unstable compared to the O-B method

Multiple linear regression M1 temperature bias correction works very well. Shown for Rayleigh-clear data for 4-13 April 2020

Without M1 bias correction



With M1 bias correction



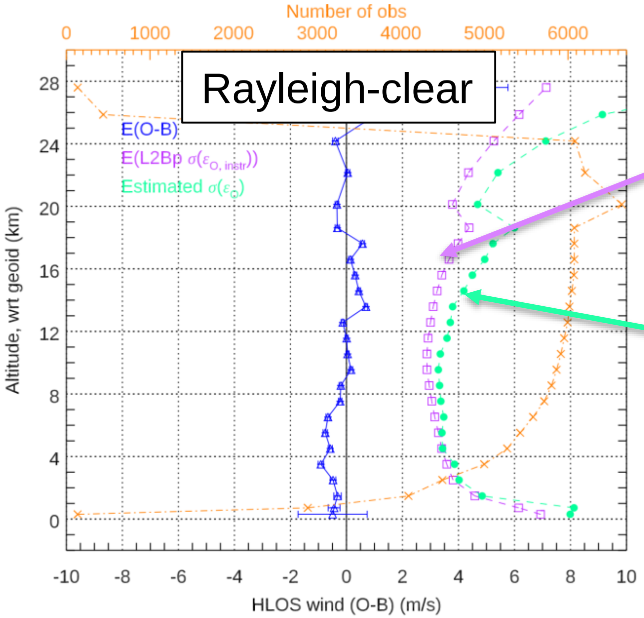
- Orbit phase dependence of bias successfully removed
- Global stdev(O-B) improved by ~0.6 m/s
- Global offset bias of -3.5 m/s removed

Topic 2: Aeolus L2B HLOS wind random errors and assignment in data assimilation

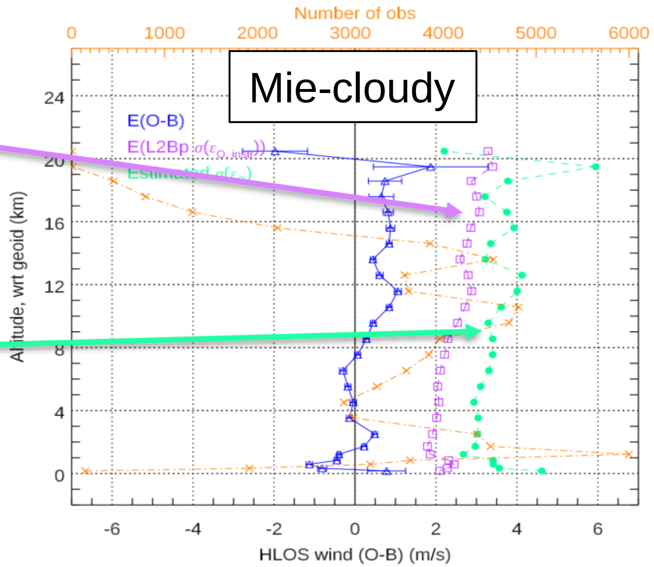
Each L2B wind observation comes with a dynamic instrument noise error estimate

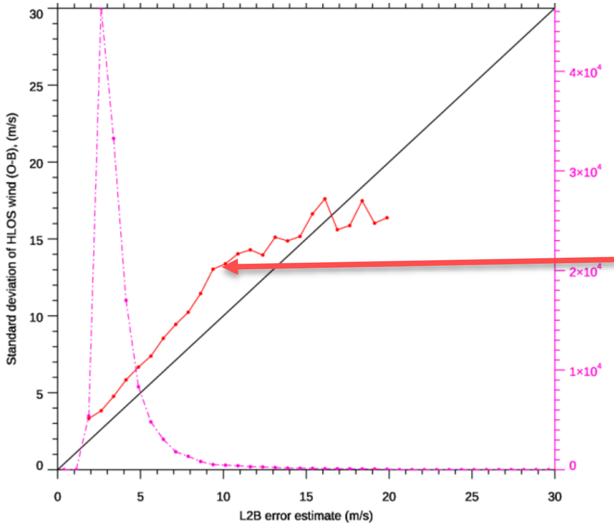
- Errors are dominated by spectrometer count shot-noise (Poisson distributed)

- L2Bp instrument noise is derived via *propagation of uncertainty* from spectrometer counts to HLOS wind; see L2Bp **A**lgorithm **T**heoretical **B**asis **D**ocument https://confluence.ecmwf.int/display/AEOL/L2B+processor+documentation+and+datasets.

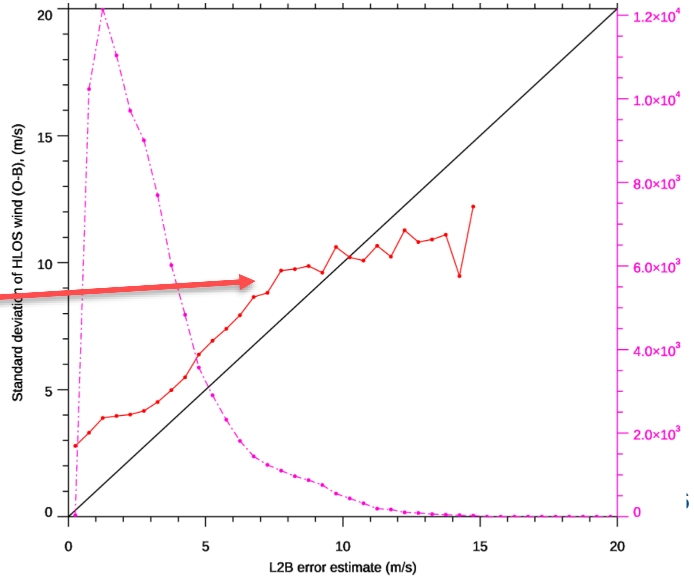


L2Bp estimated instrument noise correlates well with the observation random error (via O-B statistics)

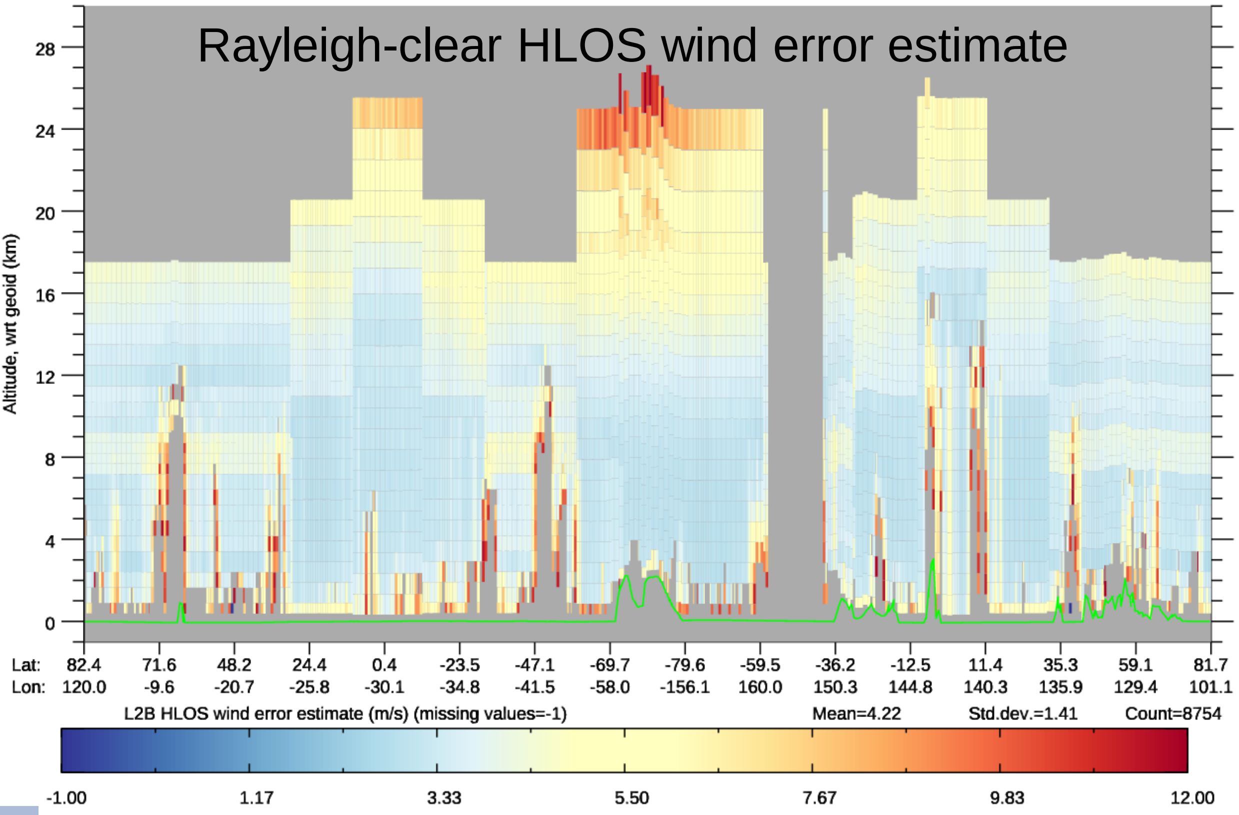


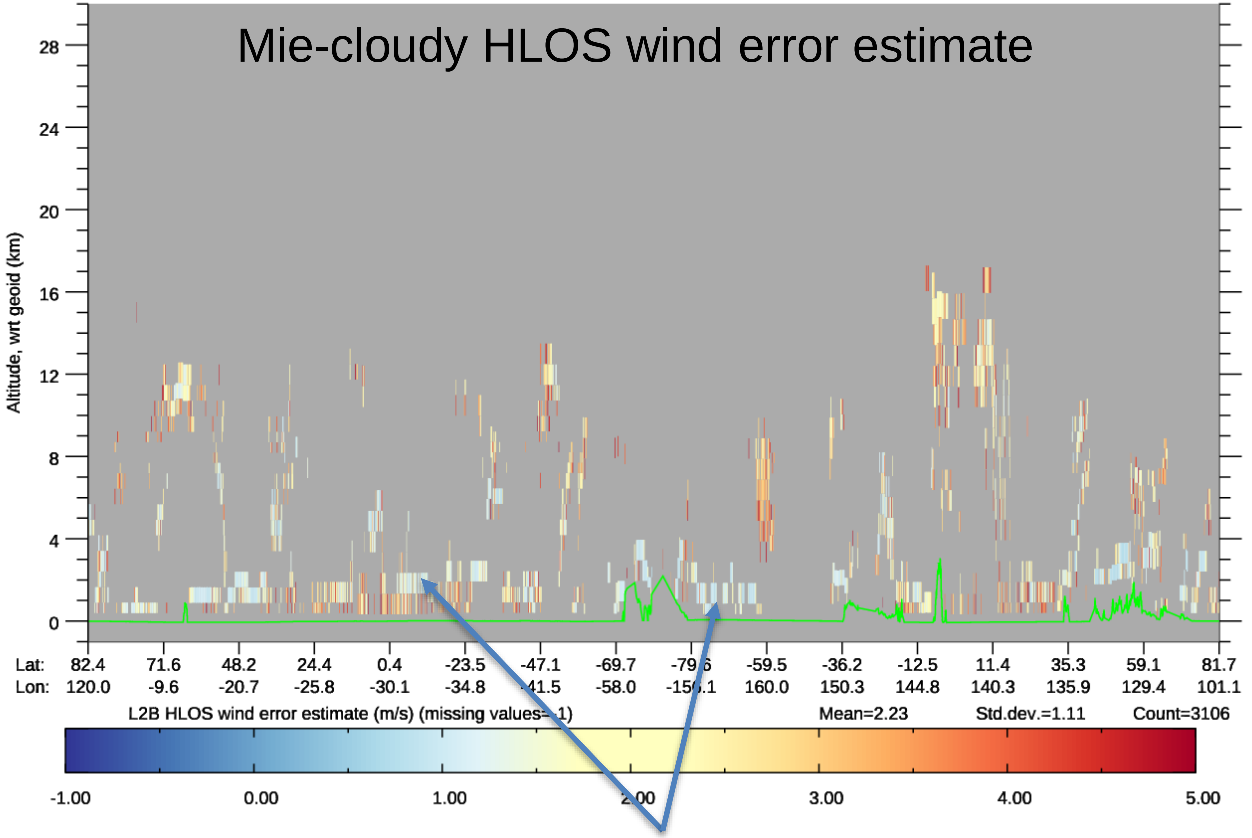


Good correlation between L2Bp instrument noise estimate and stdev(O-B)



Example of the L2B processor instrument noise estimate along an orbit



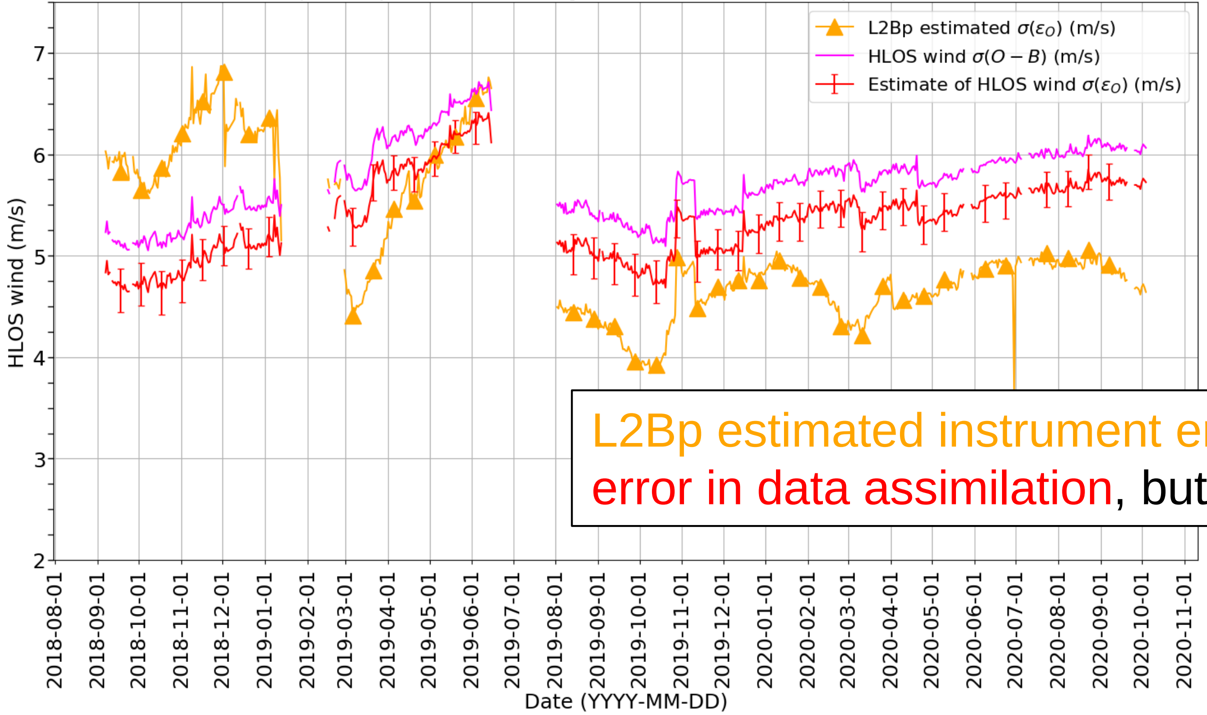


Range-bin thickness has a large affect on Rayleigh wind noise

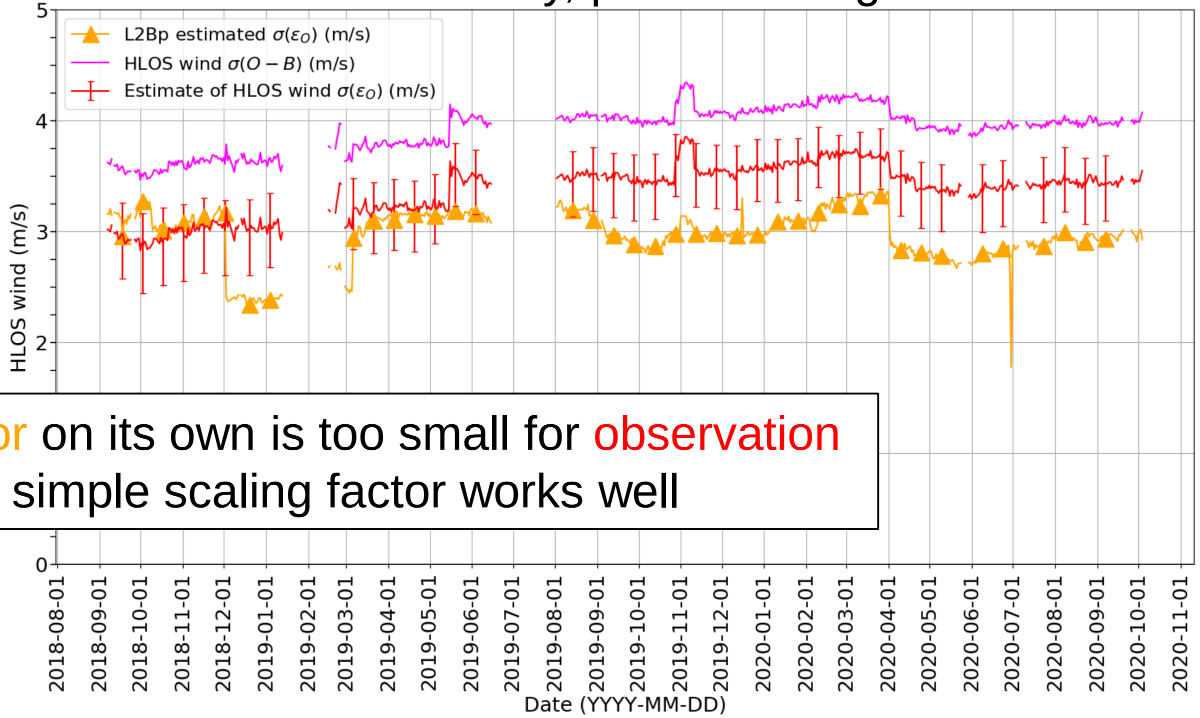
Smaller Mie wind error from strong backscatter for PBL clouds

Random errors throughout the Aeolus mission so far

Rayleigh-clear, profile average



Mie-cloudy, profile average



L2Bp estimated instrument error on its own is too small for observation error in data assimilation, but a simple scaling factor works well

Typical values for observation error $\sigma(\epsilon_O)$ based on $\sqrt{Var(O-B)-Var(\epsilon_B)}$

Wind type/pressure range	1-σ observation error estimate (ms^{-1})
Mie-cloudy/PBL	3.0
Mie-cloudy/free-troposphere	3.0-3.5
Rayleigh-clear/free-troposphere	4.0-5.5
Rayleigh-clear/lower-stratosphere	4.0-6.5

Twice as noisy a **mission requirements** – because Aeolus radiometric performance has been significantly lower than expected

Assigned observation error in data assimilation at ECMWF

- HLOS wind assigned observation error (m/s):
  - Best NWP impact was found by scaling the L2Bp instrument noise error estimate and accounting for representativeness error for Mie-cloudy only
    - $\sigma(\varepsilon_{O,assign}) = \sqrt{\alpha^2\sigma^2(\varepsilon_{O,instr}) + \sigma^2(\varepsilon_{O,rep})}$
  - Mie-cloudy winds are much finer resolution (~12 km) than the Rayleigh-clear (~87 km) and also strong backscatter from cloud can be very small scale
  - Parameters were found using a combination of simple estimates via O-B statistics, Desroziers diagnostics and OSE impact; ended up with

Wind type	L2Bp instrument error estimate scaling factor	Representativeness error (ms^{-1})
Rayleigh-clear	1.40	0
Mie-cloudy	1.25	2

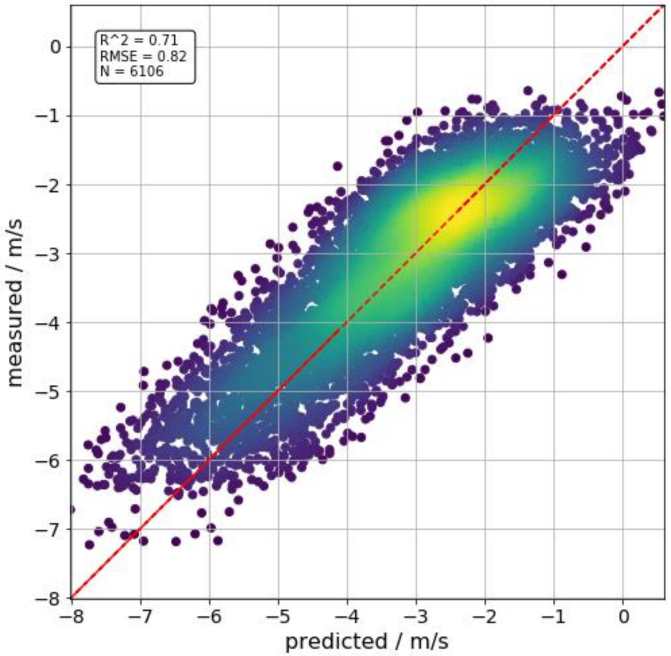
Summary

- O-B departures were key to determining a dominant source of systematic error for Aeolus winds i.e. ***primary mirror temperature gradient dependent bias*** – and to correcting it NRT processing (since 20 April 2020)
- This allowed ESA to publicly release the L2B wind data and for NWP centres to assimilate the data operationally
- Each Aeolus HLOS wind observation has an instrument noise estimate which, after scaling, can be used as the observation error for data assimilation purposes
  - Works well; contributing to the good NWP impact obtained from assimilating Aeolus data

Thanks for listening. Any questions?

Example of the operational multiple linear regression (by Fabian Weiler (DLR))

All thermistors regression



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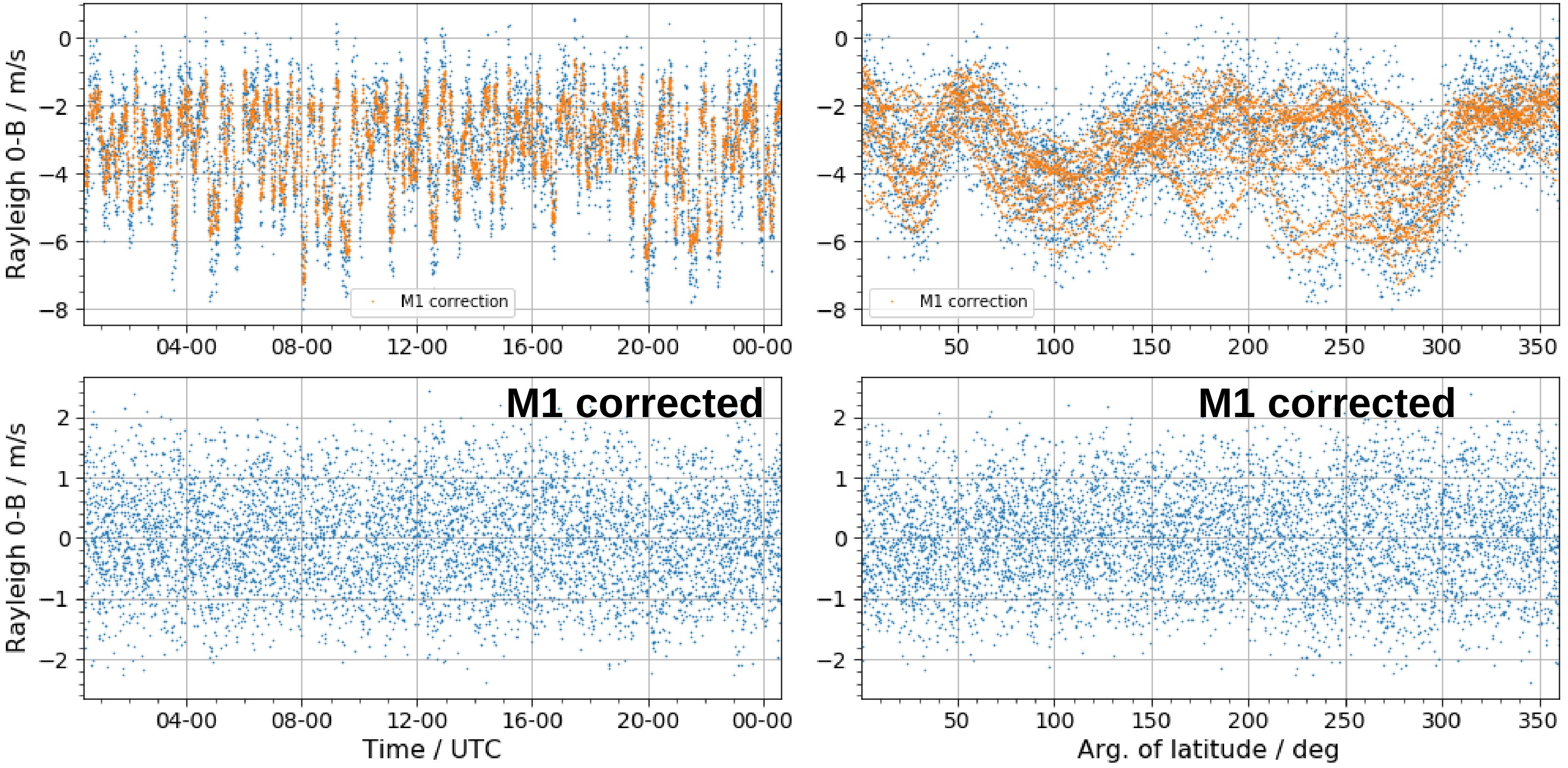
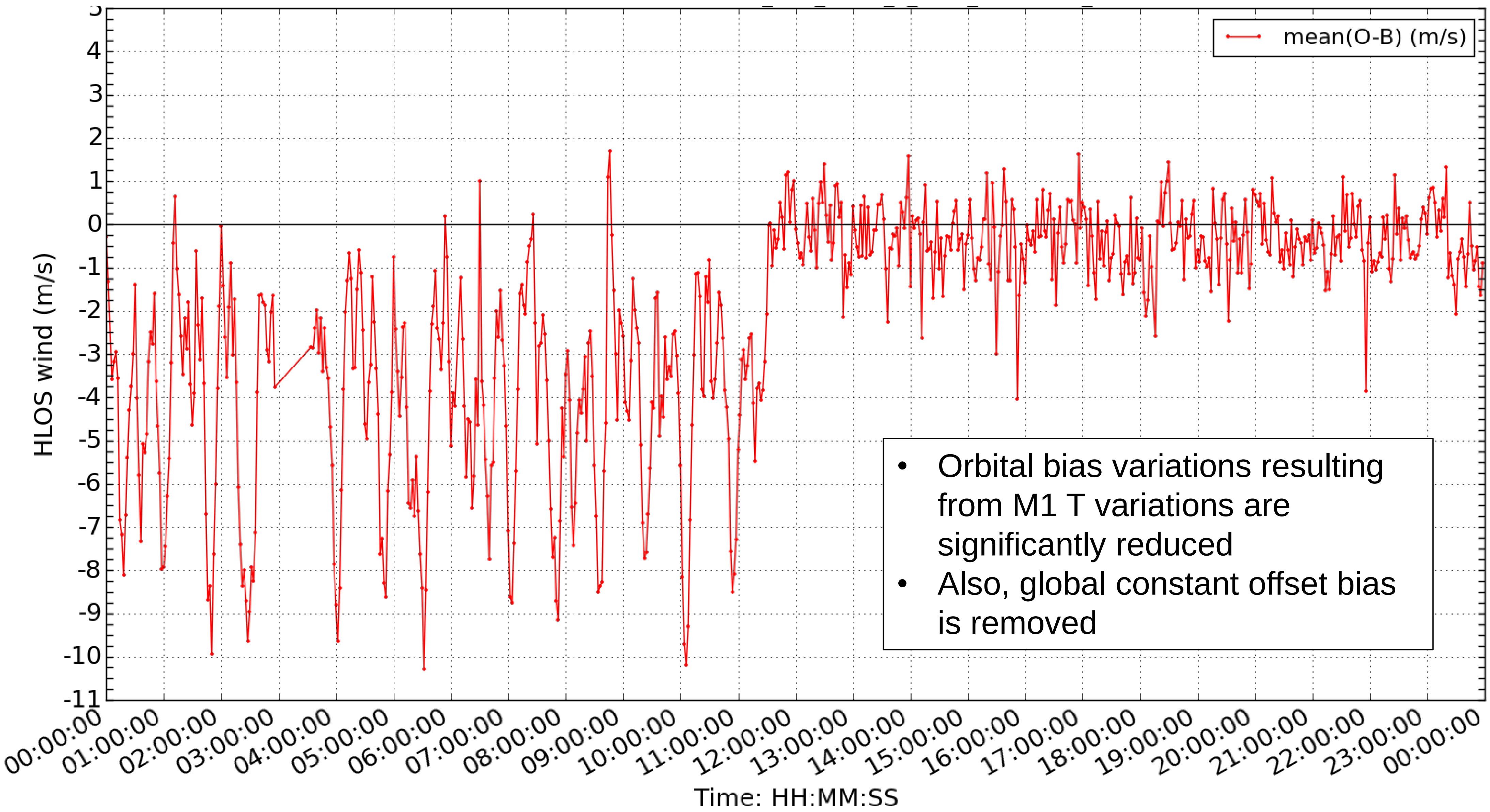


Effects of M1 correction:

1. flattens out orbital variation – reduces std. deviation of O-B (here: 1.51 m/s to 0.82 m/s)
2. Corrects for the bias drift (here: -3.25 m/s to 0 m/s)

Rayleigh-clear mean(O-B) every 2 mins on 20 April 2020 – the day the M1 bias correction went operational



- Orbital bias variations resulting from M1 T variations are significantly reduced
- Also, global constant offset bias is removed