Validation of the Aeolus wind observations in the tropics using the ALADIN Airborne Demonstrator and the 2-µm Doppler wind lidar

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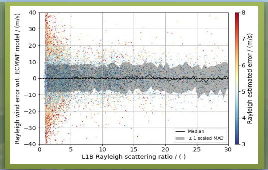
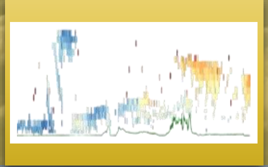
OUTLINE

The AVATAR-T campaign in September 2021



Aeolus error assessment and influence of QC



Improvement of the Mie-cloudy winds

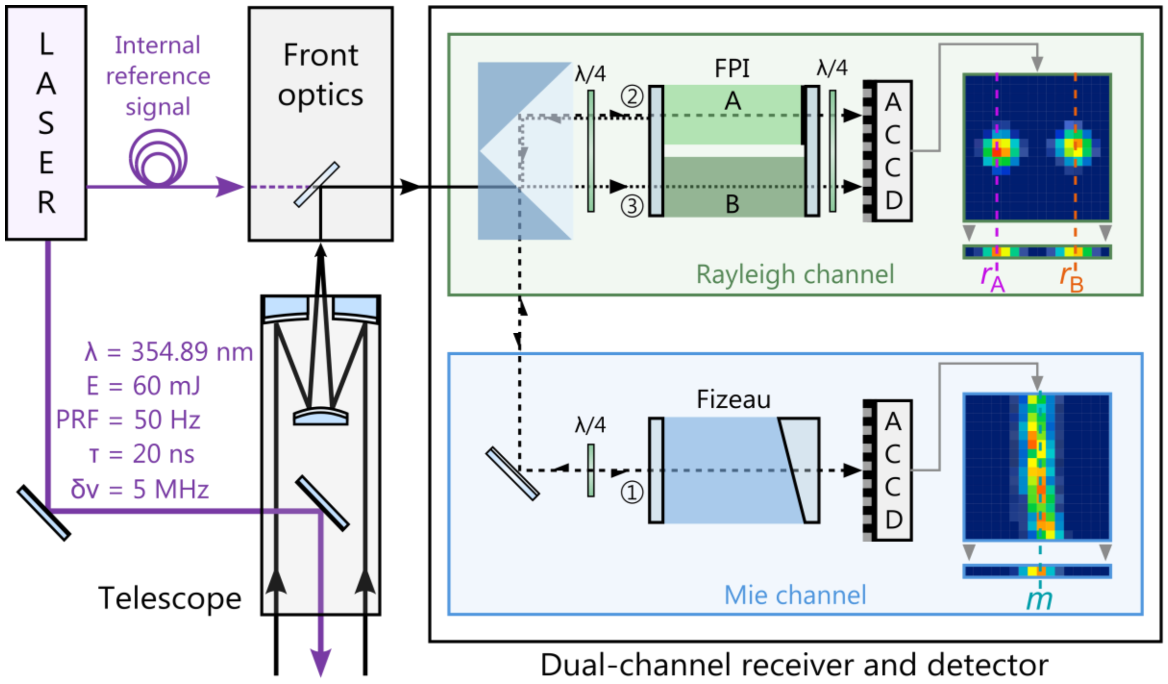
Summary and conclusions

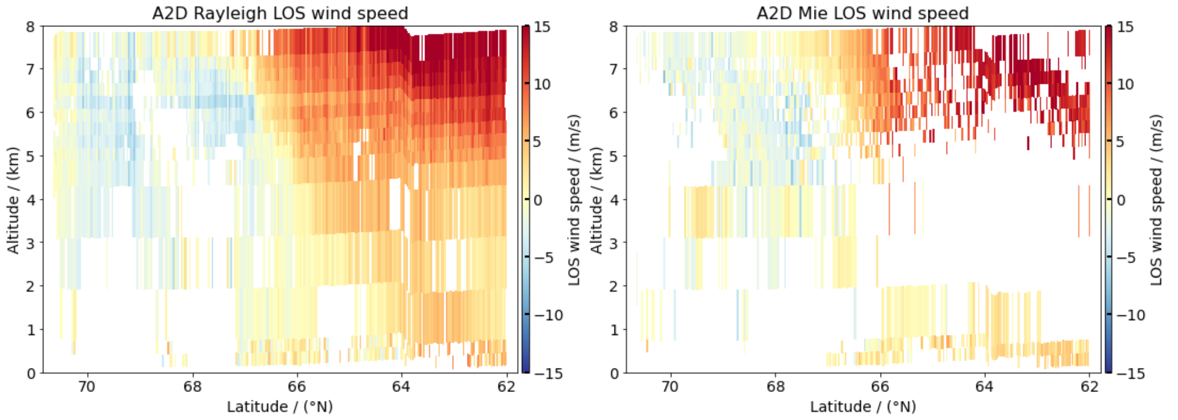
The AVATAR-T campaign in September 2021

The ALADIN Airborne Demonstrator

- A2D as a **testbed for Aeolus instrument and processor** due to its high degree of commonality with the satellite instrument
- **Rayleigh and Mie channel** for sensing the Doppler shift from molecules as well as particles (aerosols, clouds)
- Continuous **improvement of the A2D hardware and refinement of analysis methods** relevant for Aeolus

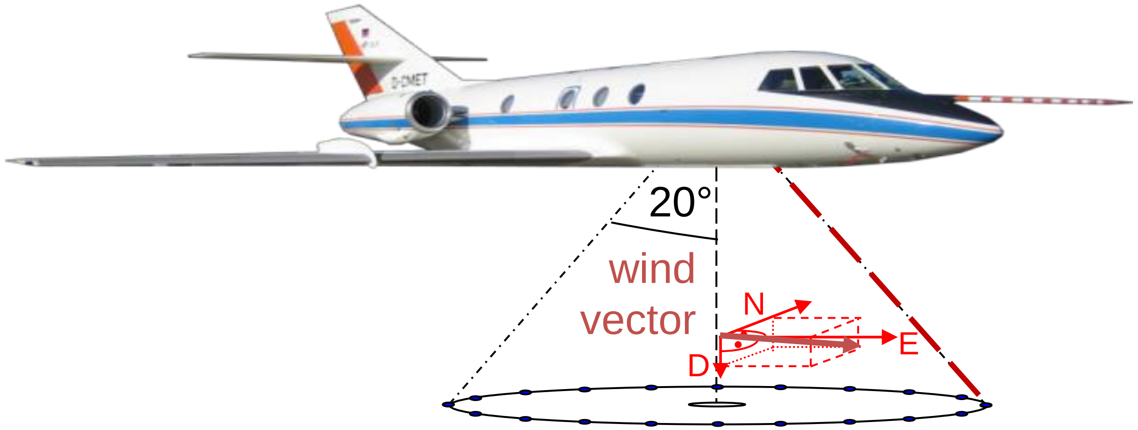
Parameter	ALADIN	ALADIN Airborne Demonstrator (A2D)
Laser wavelength	354.8 nm	354.89 nm
Repetition rate	50.5 Hz	50 Hz
Pulse energy	50…90 mJ	60 mJ
Linewidth	30 MHz (FWHM)	50 MHz (FWHM)
Telescope diameter	1.5 m	0.2 m
LOS slant angle	35°	20°
Optical layout	Transceiver configuration	Separate transmit and receive paths with active co-alignment
Receiver	Sequential Fabry-Pérot interferometers for molecular backscatter (Rayleigh channel) and Fizeau interferometer for particulate backscatter (Mie channel)	
Horizontal resolution	87 km / 10 km	3.6 km
Vertical resolution	250 m to 2000 m depending on range gate setting	300 m to 1200 m depending on range gate setting
Systematic Error	< 0.5 m/s HLOS	< 0.5 m/s LOS
Random Error	4…5 m/s HLOS (Mie) 5…8 m/s HLOS (Rayleigh)	1.5 m/s LOS (Mie) 1.8 m/s LOS (Rayleigh)



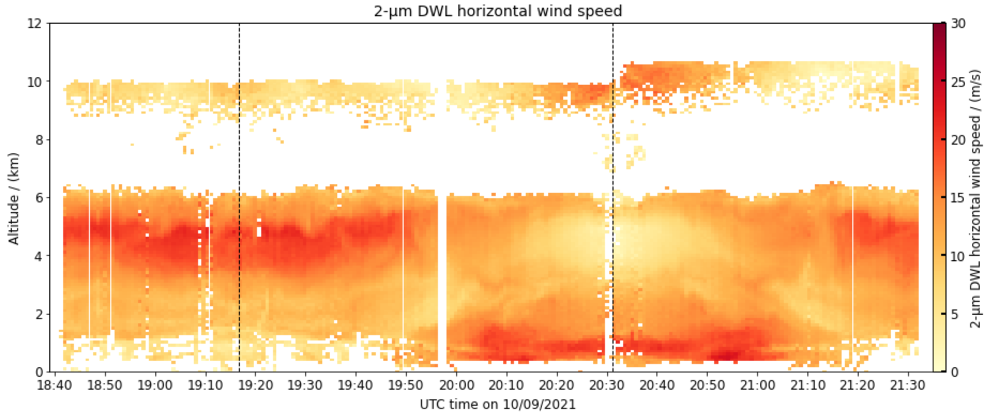


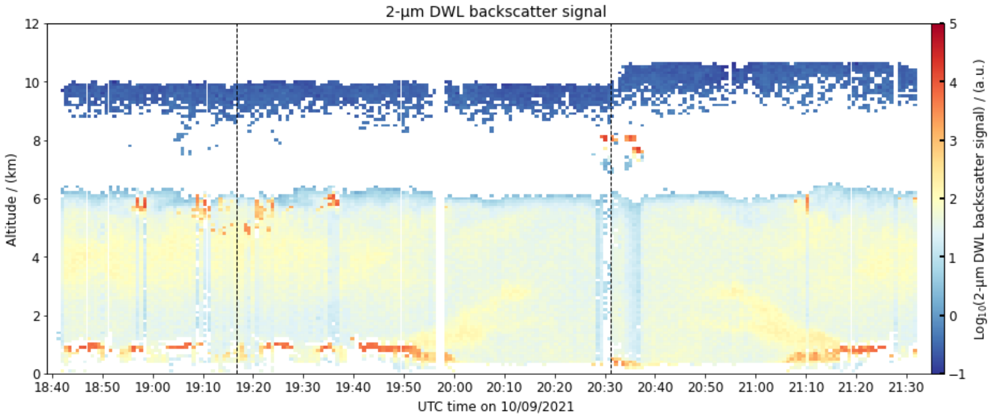
Reitebuch et al., JTECH (2009); Lemmerz et al., Appl. Opt. (2017); Lux et al., AMT (2018); Marksteiner et al., Remote Sens. (2018); Lux et al., AMT (2020); Lux et al., AMT (2022a)

2-µm heterodyne-detection Doppler wind lidar



Parameter	DLR 2-µm DWL
Detection principle	Heterodyne detection
Scanning	Double-wedge scanner
Wavelength	2022.54 nm
Laser energy	1-2 mJ
Pulse repetition rate	500 Hz
Pulse length	400-500 ns (FWHM)
Telescope diameter	10.8 cm
Vertical resolution	100 m
Temporal averaging raw data (horizontal)	single shot = 2 ms
Temporal averaging product (horizontal)	1 s per LOS (500 shots), 42 s scan (21 LOS)
Horizontal resolution	0.2 km LOS, 8.4 km wind vector
Precision (random error)	~ 1 m/s





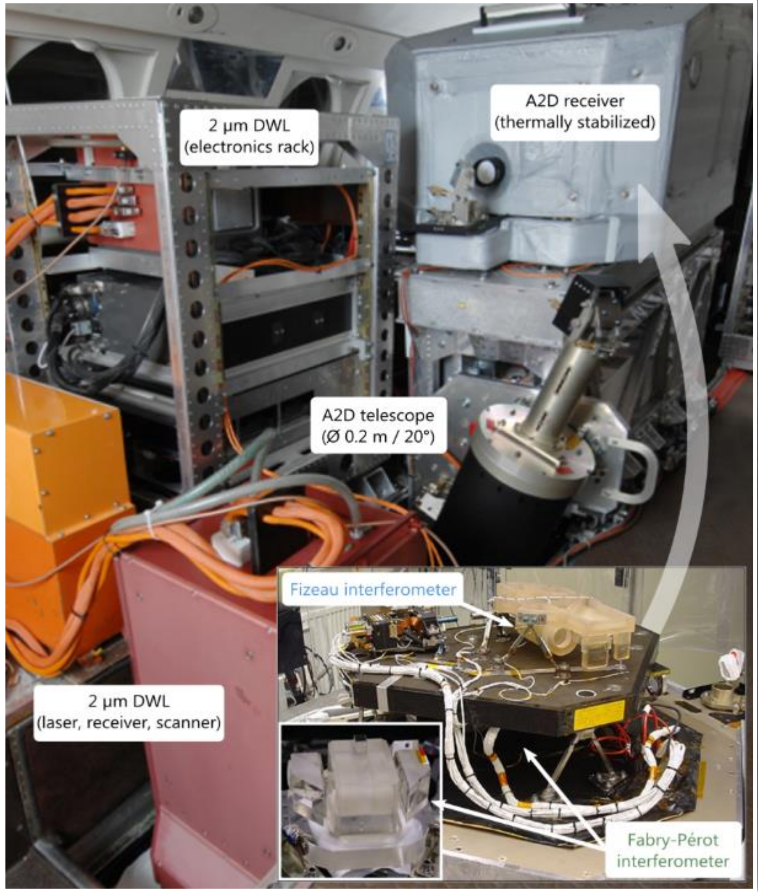
- Sampled volume varies with distance
- Constant wind field assumed
- Movement of the scanner wedges takes about 1 s
  - Horizontal resolution: ~8.4 km (~42 s) / 42 km (5 scans)
  - Vertical resolution: 100 m / 500 m
  - Random error: ~1 m/s, ~3.6°
  - Systematic error: < 0.1 m/s

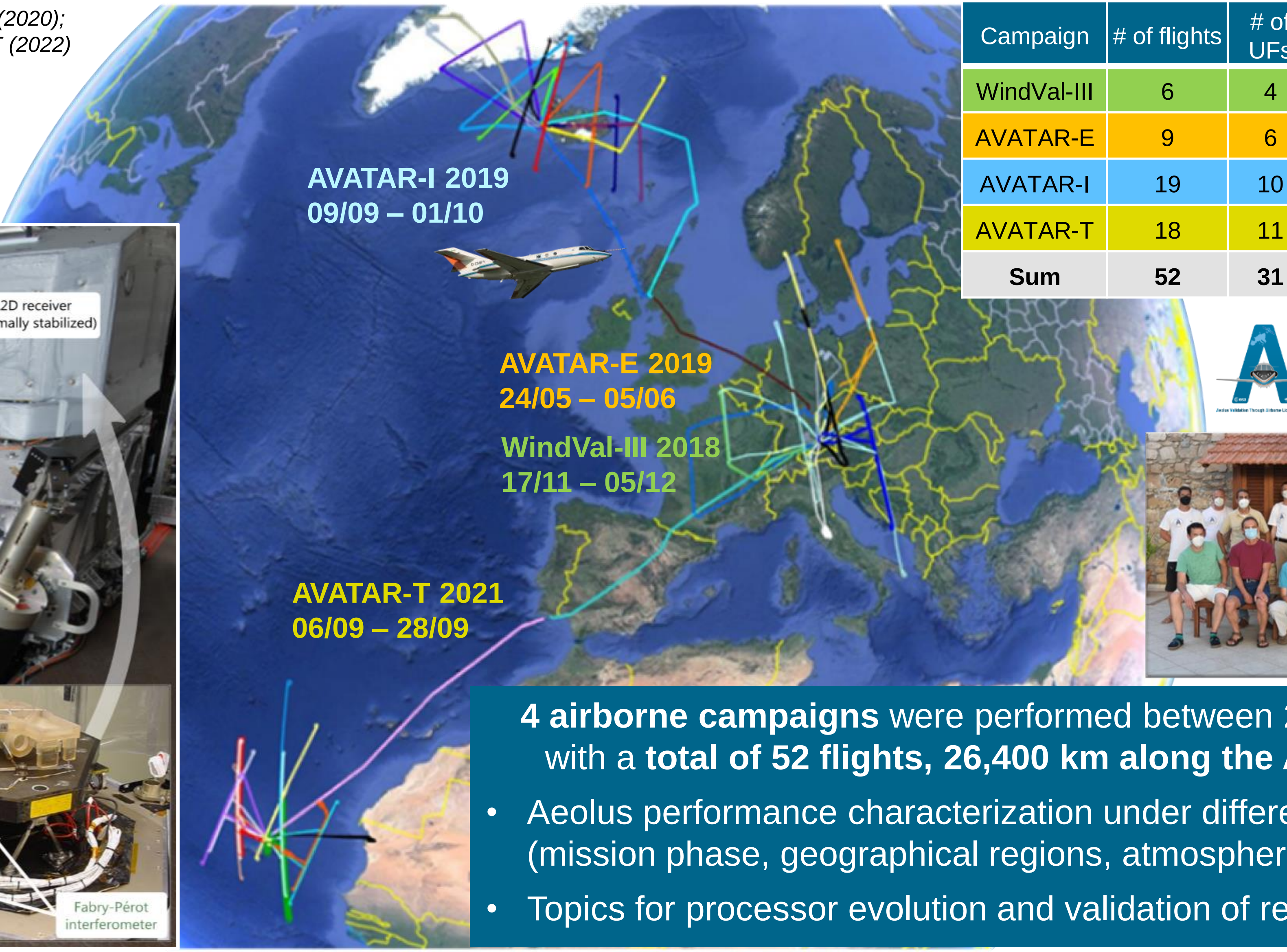
Witschas et al., JTECH (2017); Witschas et al., AMT (2020); Witschas et al., AMT (2022)

Airborne validation campaigns during the Aeolus mission

Lux et al., AMT (2020); Witschas et al., AMT (2020);
Lux et al., AMT (2022a); Witschas et al., AMT (2022)

Instrumentation in the DLR Falcon aircraft





Campaign	# of flights	# of UFs	Sat track/km	Total flight hours
WindVal-III	6	4	3,000	24
AVATAR-E	9	6	4,400	36
AVATAR-I	19	10	8,000	61
AVATAR-T	18	11	11,000	69
Sum	**52**	**31**	**26,400**	**190**

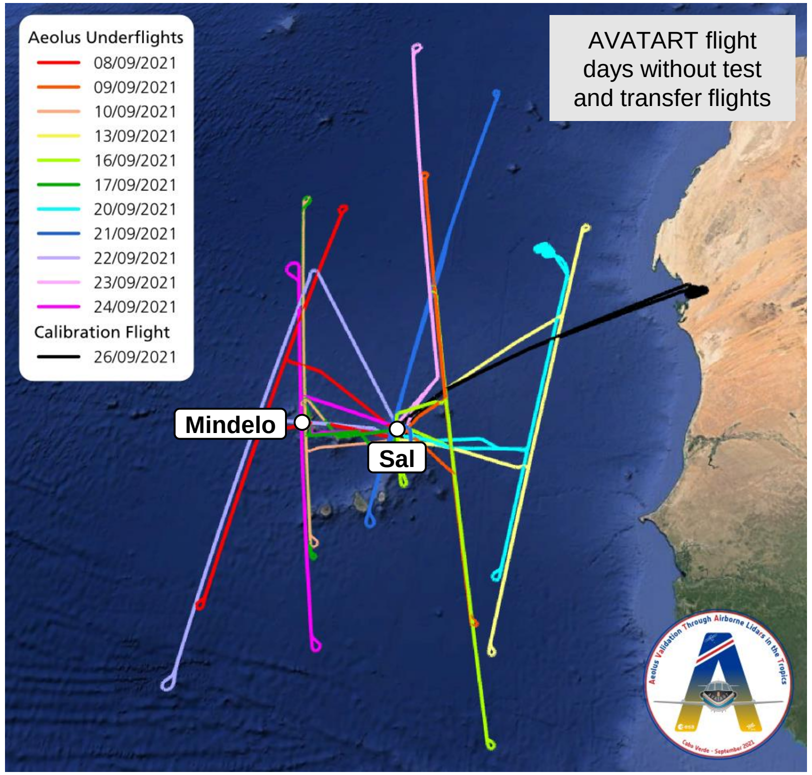
4 airborne campaigns were performed between 2018 and 2021 with a **total of 52 flights, 26,400 km along the Aeolus track**

- Aeolus performance characterization under different conditions (mission phase, geographical regions, atmospheric dynamics)
- Topics for processor evolution and validation of reprocessed data

Overview of AVATAR-T flights

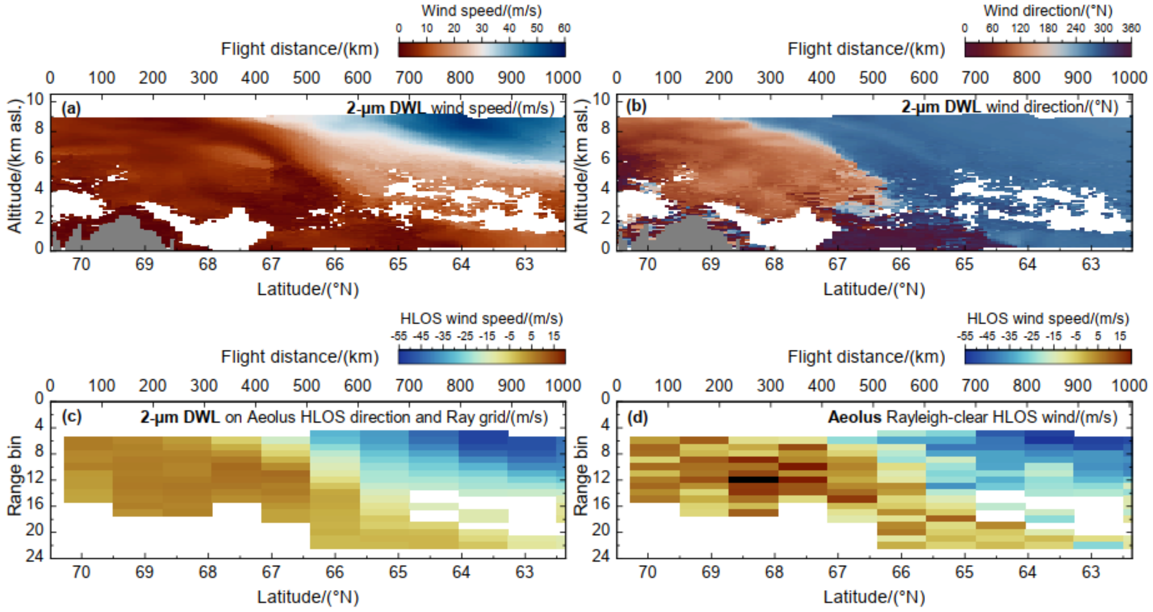
Date	Time (UTC)	Objective	Start/stop times and locations of the Aeolus overpasses		Length of underflight leg	Number of Aeolus BRCs	Mindelo overpasses
04/09	08:08 – 12:07	Test flight	-		-	-	-
06/09	08:08 – 10:58	Transfer flight	-		-	-	-
06/09	12:06 – 16:06	Transfer flight	-		-	-	-
08/09	05:44 – 09:28	Aeolus underflight #1	07:39:49 UTC 22.5°N, 25.1°W	07:42:13 UTC 13.0°N, 26.8°W	886 km	10	09:01 UTC
09/09	17:25 – 21:23	Aeolus underflight #2	19:22:20 UTC 12.6°N, 21.0°W	19:25:08 UTC 23.5°N, 23.0°W	1242 km	15	-
10/09	18:20 – 22:05	Aeolus underflight #3	19:36:01 UTC 14.1°N, 24.6°W	19:38:13 UTC 23.0°N, 26.2°W	910 km	11	18:53 UTC **19:37 UTC** 21:29 UTC
13/09	05:35 – 08:18	Aeolus underflight #4	07:14:25 UTC 22.0°N, 18.6°W	07:16:55 UTC 11.9°N, 20.6°W	1048 km	12	-
16/09	17:09 – 21:04	Aeolus underflight #5	19:21:42 UTC 10.1°N, 20.5°W	19:24:15 UTC 20.3°N, 22.4°W	1002 km	12	-
17/09	18:06 – 21:58	Aeolus underflight #6	19:35:33 UTC 13.9°N, 24.6°W	19:38:13 UTC 23.0°N, 26.2°W	975 km	11	18:41 UTC, **19:37 UTC** 21:29 UTC
20/09	06:58 – 10:30	Aeolus underflight #7 + Calibration flight #1	07:14:42 UTC 20.6°N, 19.2°W	07:16:32 UTC 13.5°N, 20.5°W	707 km	8	-
21/09	05:09 – 09:12	Aeolus underflight #8	07:26:08 UTC 26.4°N, 21.3°W	07:29:03 UTC 14.7°N, 23.4°W	1234 km	15	-
22/09	06:11 – 09:55	Aeolus underflight #9	07:40:20 UTC 20.6°N, 25.6°W	07:42:35 UTC 11.7°N, 27.2°W	950 km	11	9:27 UTC
23/09	18:05 – 21:39	Aeolus underflight #10	19:23:42 UTC 18.0°N, 22.2°W	19:26:10 UTC 28.3°N, 24.1°W	1054 km	12	-
24/09	17:36 – 21:18	Aeolus underflight #11	19:35:29 UTC 12.0°N, 24.3°W	19:37:42 UTC 21.0°N, 25.9°W	935 km	11	18:09 UTC, **19:37 UTC** 20:51 UTC
26/09	13:30 – 17:02	Calibration flight #2	-		-	-	-
28/09	08:02 – 10:08	Transfer flight	-		-	-	-
28/09	13:23 – 15:06	Transfer flight	-		-	-	-
28/09	15:55 – 18:36	Transfer flight	-		-	-	-

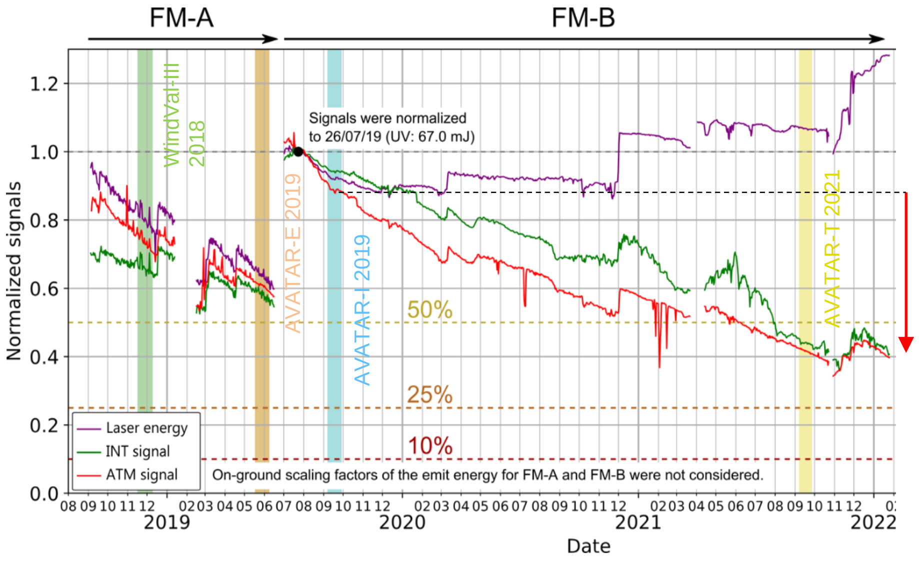
- **18 flights with 69 flight hours** including 1 test, 5 transfer and 1 calibration flight
- 42.5 flight hours for **11 Aeolus underflights** (6 along ascending / 5 along descending orbits)
- **≈11,000 km of the Aeolus track** were covered
- Mindelo ground station was overpassed 11 times (3 overpasses in coordination with Aeolus)



Aeolus error assessment and influence of QC

Statistical comparison of Aeolus and 2-µm DWL wind data



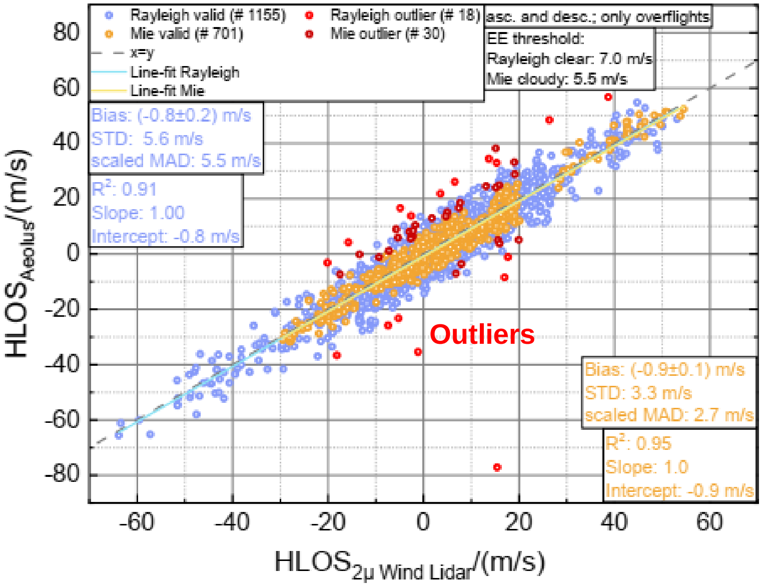


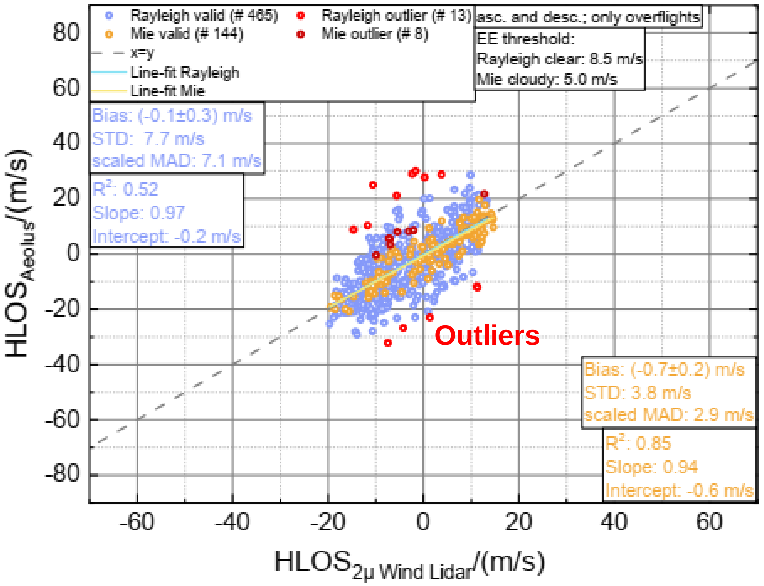
Aeolus signal evolution

AVATAR-I (2019)

Mie-cloudy
Rayleigh-clear

AVATAR-T (2021)





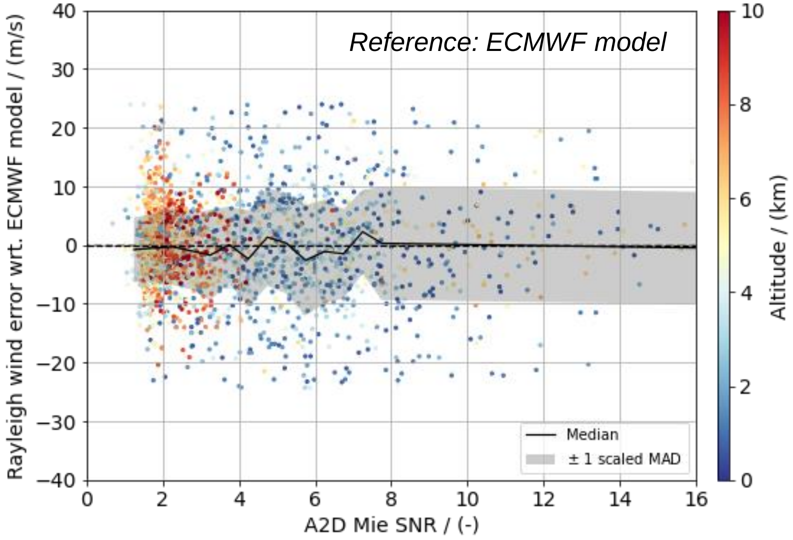
- Multiple Aeolus underflights are necessary to obtain robust statistics
- **Systematic errors of Rayleigh and Mie winds are close to the mission requirement** (<0.7 m/s)
- **Rayleigh random error has significantly increased between 2019 and 2021** from 5.5 m/s to 7.1 m/s due to the signal loss, partly mitigated by the smaller solar background in the tropics

Witschas et al., AMT (2022)

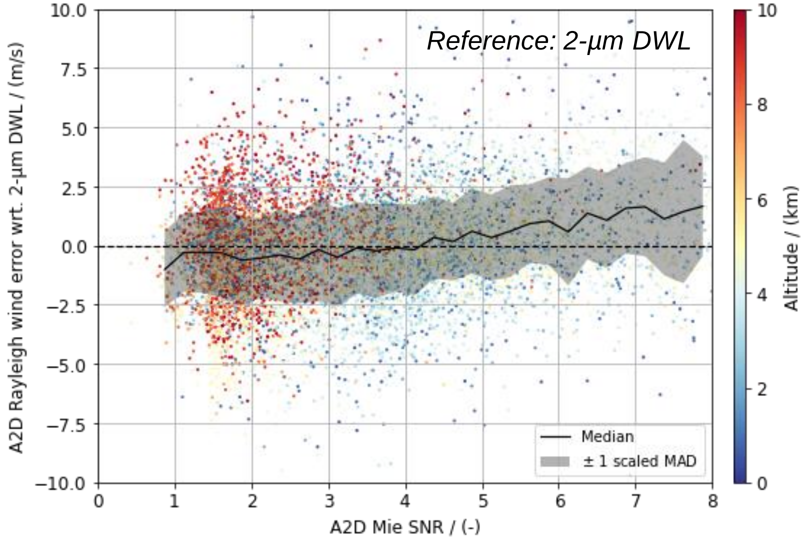
Aeolus / A2D Rayleigh wind error in dependence on scattering ratio

- **A2D and Aeolus Rayleigh wind errors** with respect to the 2-µm DWL and the ECMWF model background were determined **in dependence on the L1B scattering ratio and the A2D Mie SNR** (as a proxy for the scattering ratio)
- The **wind bias <u>does not change with SR for Aeolus</u>**, whereas it **<u>increases almost linearly</u> increases by more than 2 m/s from low to high Mie SNR <u>for the A2D</u>**
- The **positive bias at high SNR is evident over the entire altitude range**, i.e., it is **not related to altitude-dependence** of the Rayleigh wind error, although most winds with high SNR are located in the lower troposphere (aerosol layer)
- The **Aeolus Rayleigh random error increases with scattering ratio due to signal extinction in aerosol regions** (verified by 2-µm DWL comparison, see Witschas et al., AMT (2022))

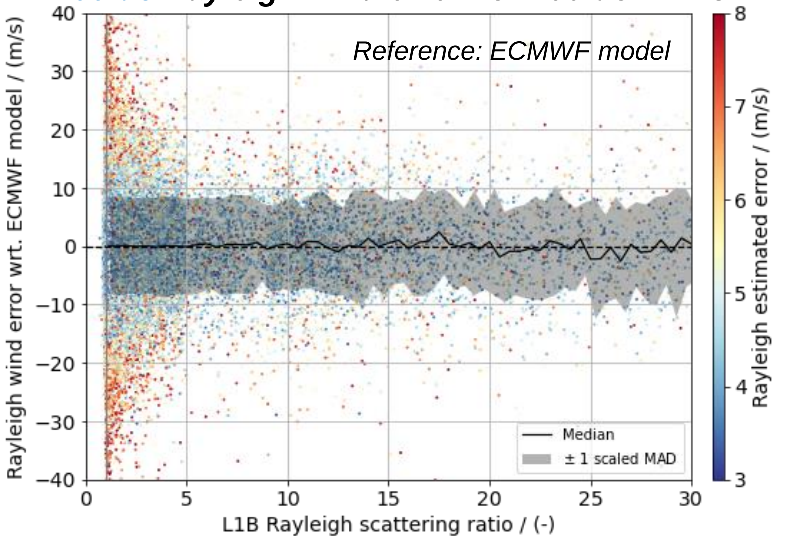
***Aeolus* Rayleigh wind error vs. A2D Mie SNR**



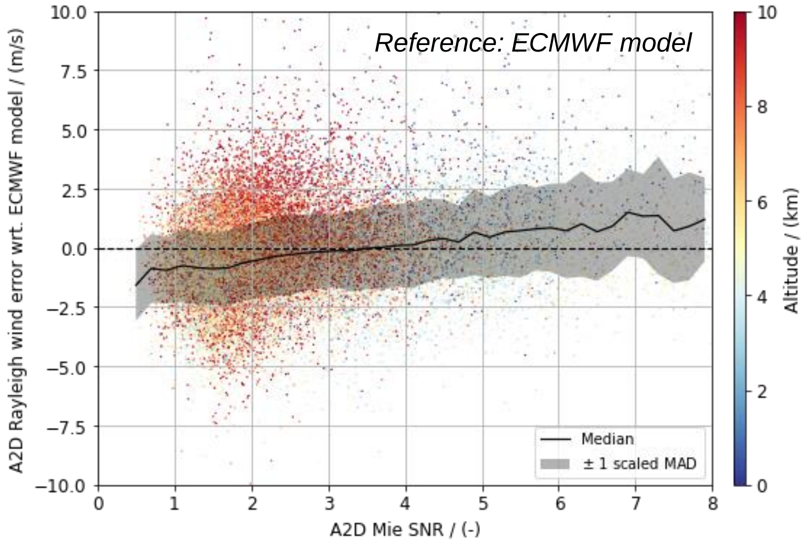
***A2D* Rayleigh wind error vs. A2D Mie SNR**



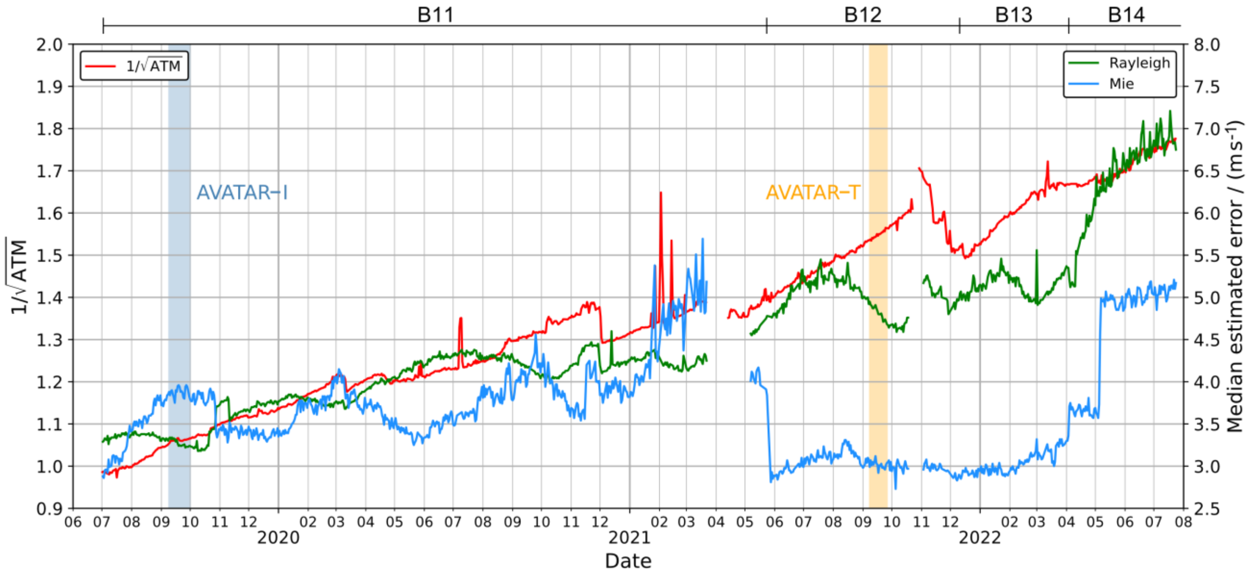
***Aeolus* Rayleigh wind error vs. Aeolus L1B SR**



***A2D* Rayleigh wind error vs. A2D Mie SNR**



Influence of quality control on the Aeolus wind data validation



- **Estimated error (EE) of the wind results provided in the L2B product is widely used as a QC criterion, but does not consider all relevant error sources**

→ *Gross errors may still be included in the dataset*

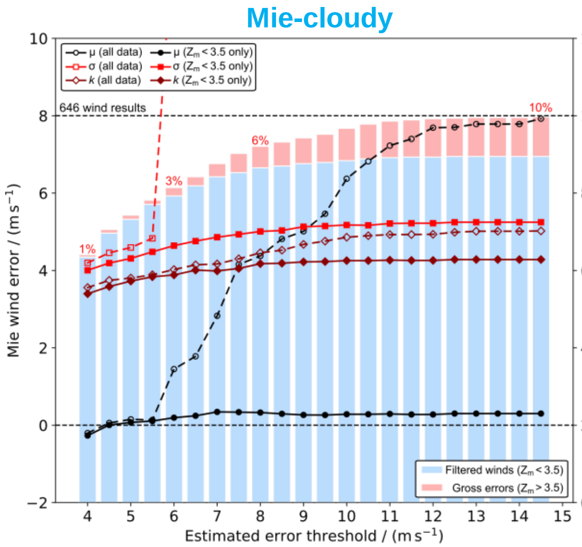
- **Large spatial and temporal variability of the EE and inconsistent choice of EE thresholds for QC**

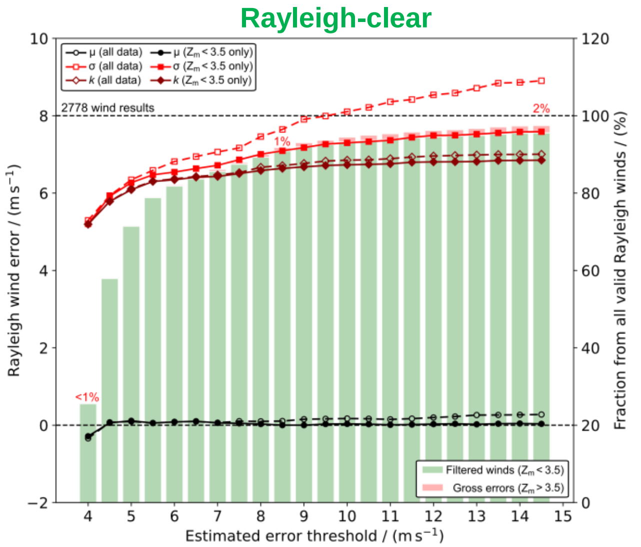
→ *Limited comparability of different validation studies*

- **Careful statistical analysis** including a **rigorous screening for outliers** is necessary to be compliant with the error definitions formulated in the Aeolus mission requirements document.
- **QC scheme based on the EE in combination with the modified Z score** (Z_m) ensures meaningful statistics

$$Z_{m,i} = \frac{x_i - x_{median}}{\text{scaled MAD}} \quad \text{with} \quad \text{scaled MAD} = 1.4826 \cdot \text{median}(|x_i - x_{median}|)$$

- Statistical approach was applied to the validation of Aeolus wind data from the AVATAR-T campaign



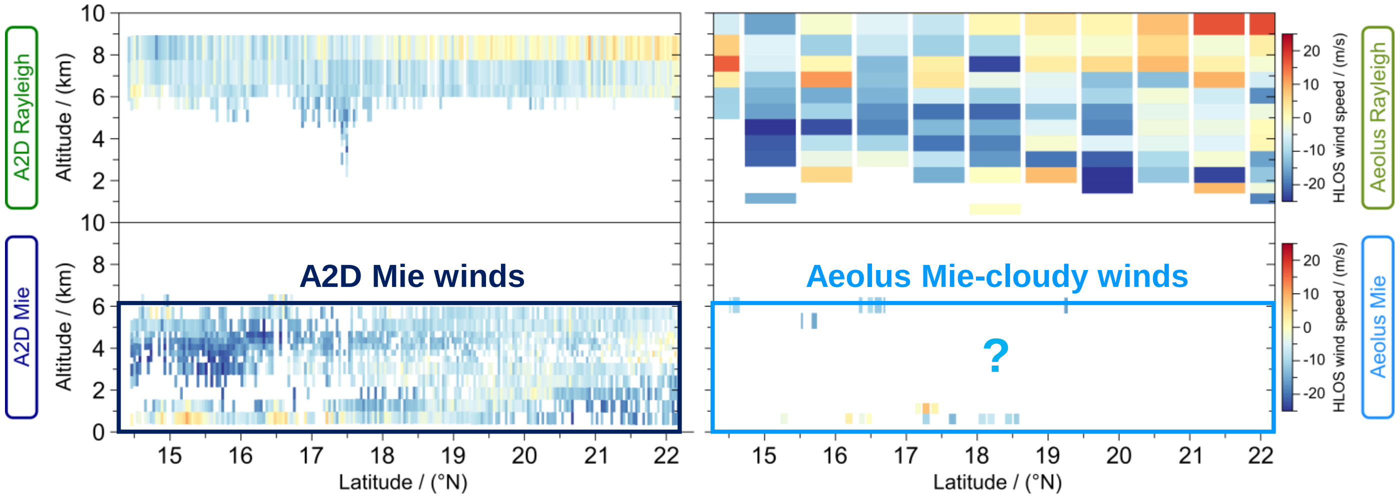


Lux et al., AMT (2022b)

Improvement of the Mie-cloudy winds

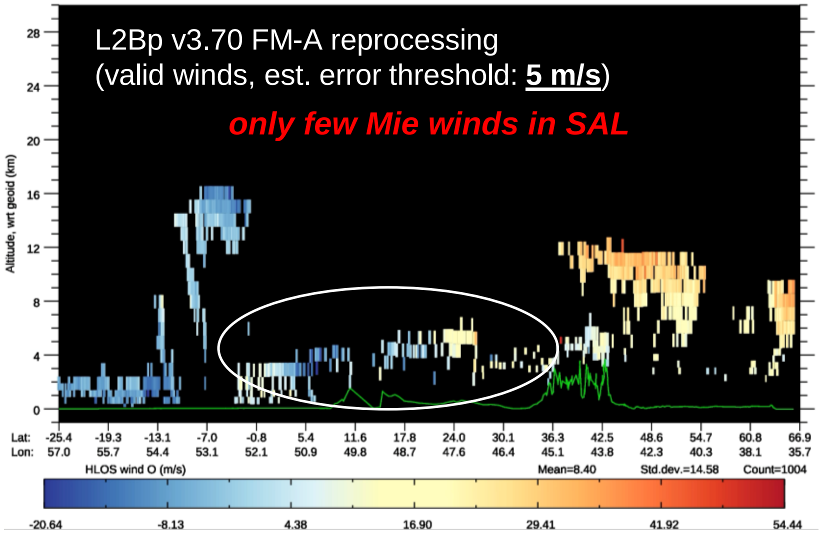
Impact of processor updates on the Mie-cloudy winds

Wind data from Aeolus and A2D Rayleigh and Mie channels from the Aeolus underflight on 10/09/2021

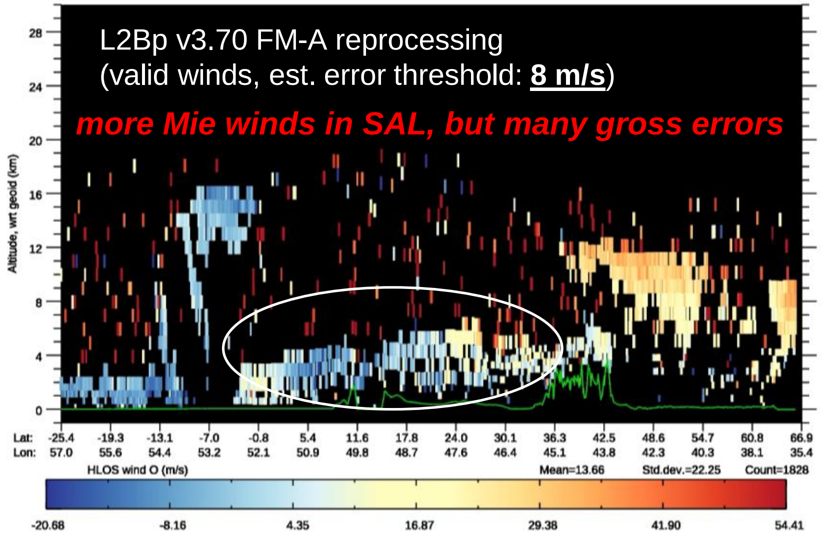


- **Lack of Aeolus Mie-cloudy winds compared to A2D and 2-µm DWL coverage in Saharan Air Layer** stimulated improvements to the L2B processor
- Implementation of a **"residual error" threshold for QC of Mie Core output and improved correction for the Rayleigh background** increases the Mie data coverage, as it allows to relax the estimated error threshold
- **New QC scheme was optimized for a test case in the tropics in 2019**, while the AVATAR-T cases in 2021 could not be significantly improved due to lower SNR of the dust compared to 2019 (signal loss)

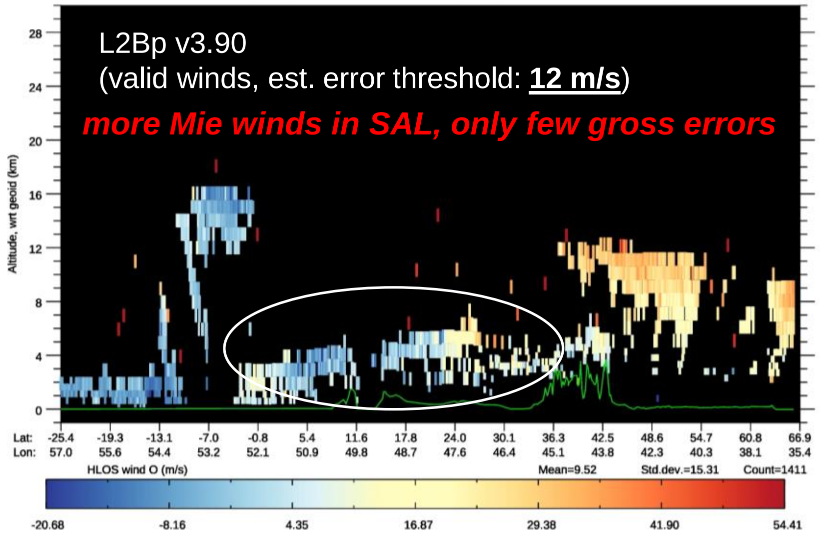
Test case from 1 May 2019 before processor updates



Test case from 1 May 2019 before processor updates



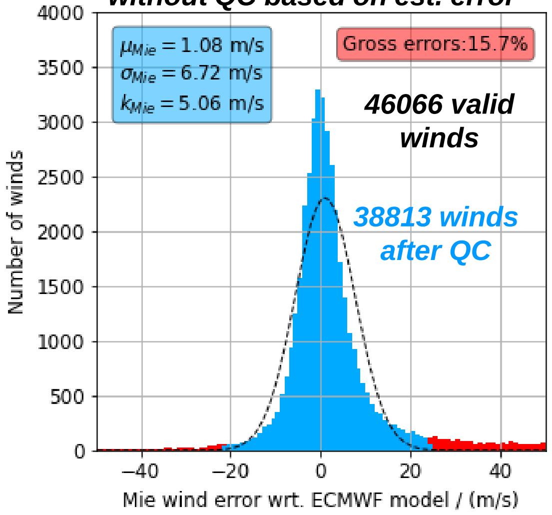
Test case from 1 May 2019 after processor updates



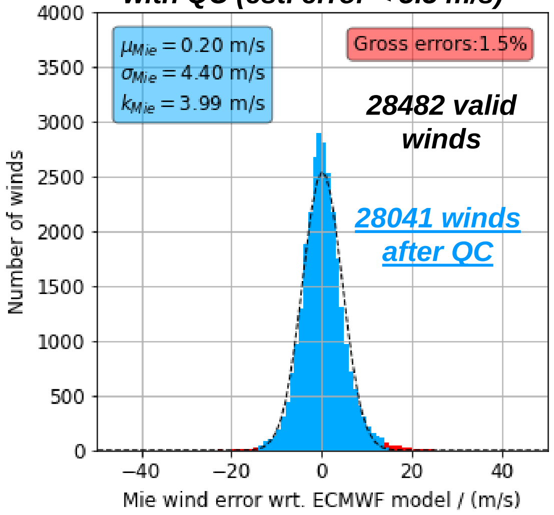
Improvement of the Mie wind data quality

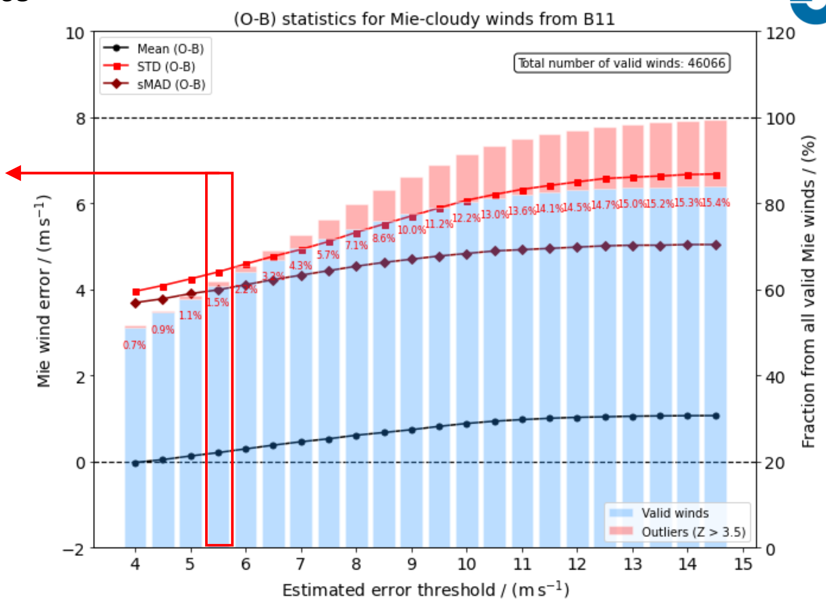
5 orbits from AVATAR-I underflights in September 2019 before processor updates

without QC based on est. error

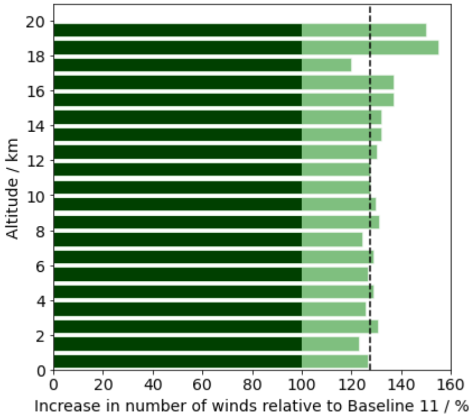


with QC (est. error < 5.5 m/s)

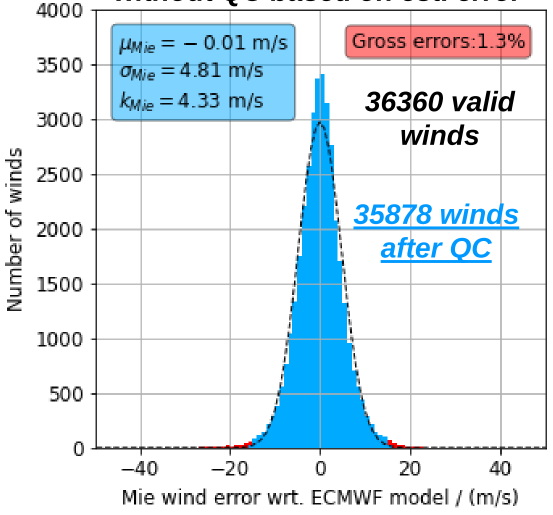


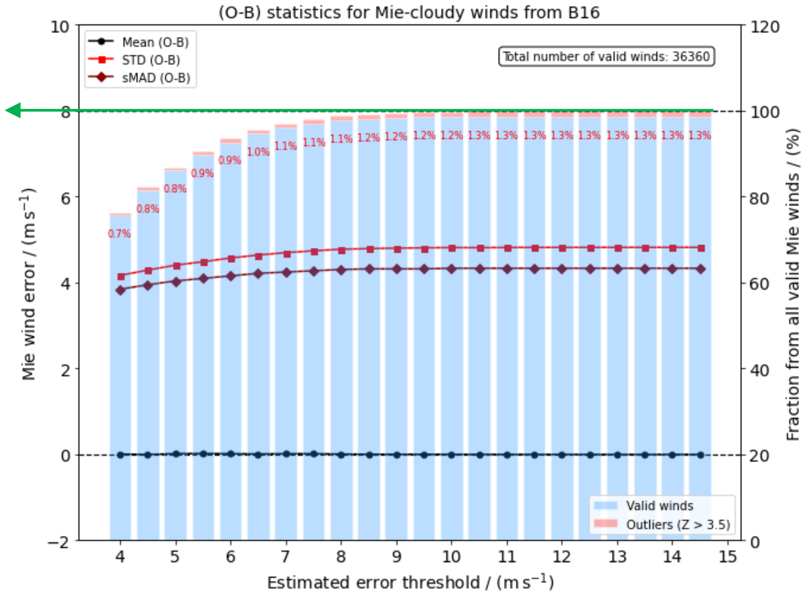


Increase in number of winds per altitude bin of 1 km



After processor updates without QC based on est. error





- Thanks to the processor updates, **gross errors are largely eliminated (<2%) for the Mie-cloudy winds even without applying an estimated error filter**.
- The **remaining few gross errors are evenly distributed**, hence the bias does not change depending on QC settings.
- At the same time, the **number of valid Mie-cloudy winds is increased by about 30%**, increase in area coverage is 15%, more or less homogeneously over all altitudes.
- The **random error is only 7% larger** (sMAD ≈ 4.3 m/s compared to 4.0 m/s) **despite preliminary processing** for test cases (Mie response calibration, Mie nonlinearity, Rayleigh background array, M1 temp. correction not updated).

Summary and conclusions

- AVATAR-T as part of the JATAC was the 4th DLR airborne campaign for Aeolus in-orbit validation deploying the A2D and 2-µm DWL to perform 11 underflights covering 11,000 km of the Aeolus track in the tropical region around Sal, Cabo Verde in September 2021.

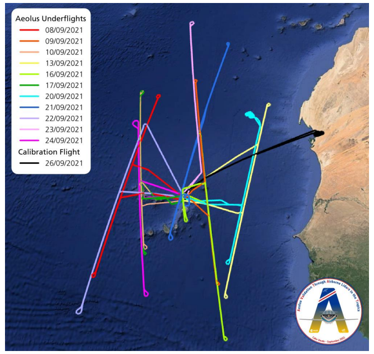
- The systematic errors of Rayleigh and Mie winds with respect to the 2-µm DWL were verified to be close to the mission requirement (<0.7 m/s), while the Rayleigh random error was as large as 7.1 m/s due to the low atmospheric backscatter signal in 2021 (Mie random error: 2.9 m/s).

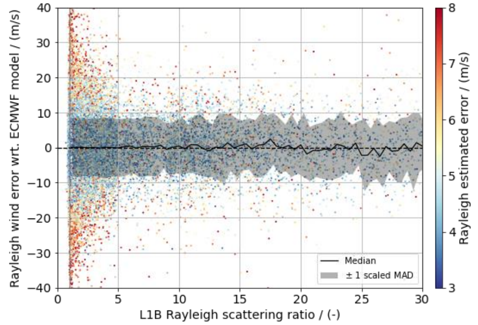
- The Aeolus Rayleigh-clear wind bias does not change with scattering ratio which is in contrast to the A2D Rayleigh winds. The increase in Rayleigh-clear random error in dust-laden areas is caused by signal attenuation rather than by Mie contamination.

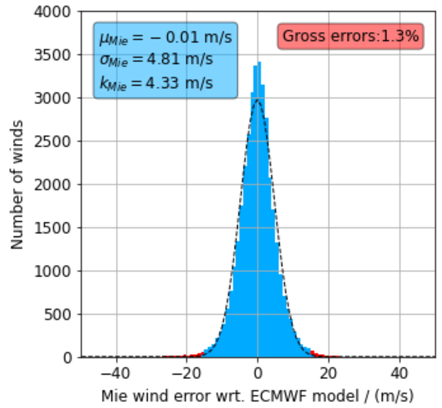
- Precise error assessment of the Aeolus winds necessitates a careful statistical analysis, including a rigorous screening for gross errors which is accomplished by the modified Z-score. The statistical approach was applied to the validation of Aeolus wind data from the AVATAR-T campaign showing a strongly skewed distribution of Mie wind errors wrt. the 2-µm DWL.

- The lack of Aeolus Mie-cloudy winds compared to the A2D Mie coverage in the SAL stimulated the ongoing development of L2B processor updates which largely eliminated gross errors while increasing the number of valid winds by about 30%.

- The NRT Mie data quality is significantly improved with the new processor baseline 16 which was released on 18 April 2023. The improvements will also take effect in the reprocessing of the entire mission dataset to be published in the next years.







Thank you for your attention!