DLR AIRBORNE AEOLUS VALIDATION CAMPAIGNS AND RESULTS

AEOLUS SCIENCE CONFERENCE - 25 MAY 2023

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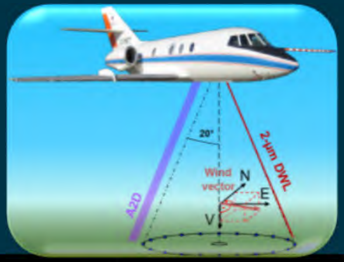
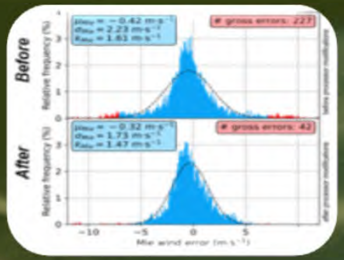
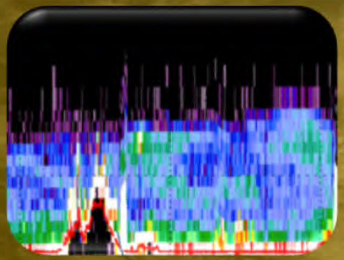
Outline



➢ AIRBORNE DOPPLER WIND LIDARS AND VALIDATION CAMPAIGNS



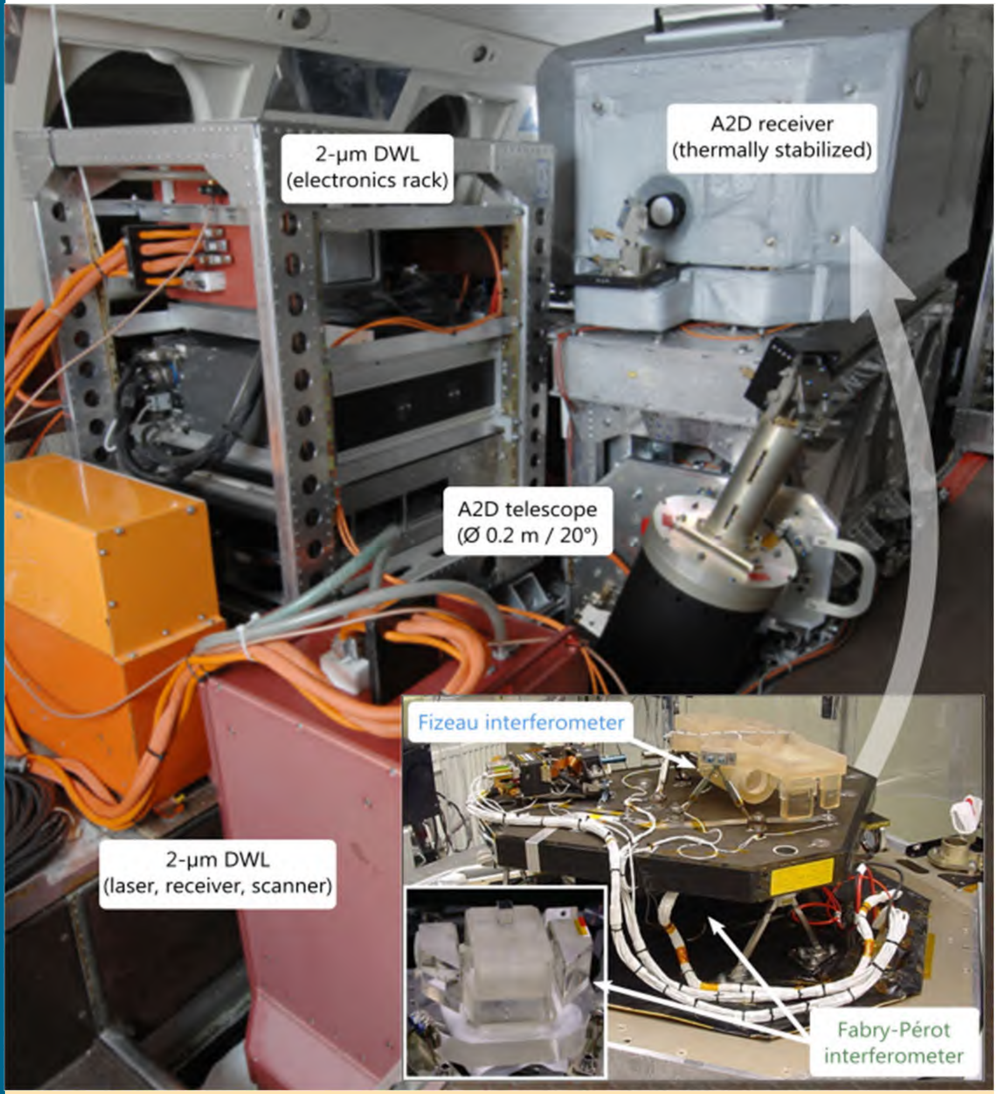
➢ CAMPAIGN RESULTS RELEVANT FOR PROCESSOR EVOLUTIONS



➢ AEORSOL TOPICS

➢ SUMMARY AND OUTLOOK

A2D and the 2-µm Doppler Wind Lidars

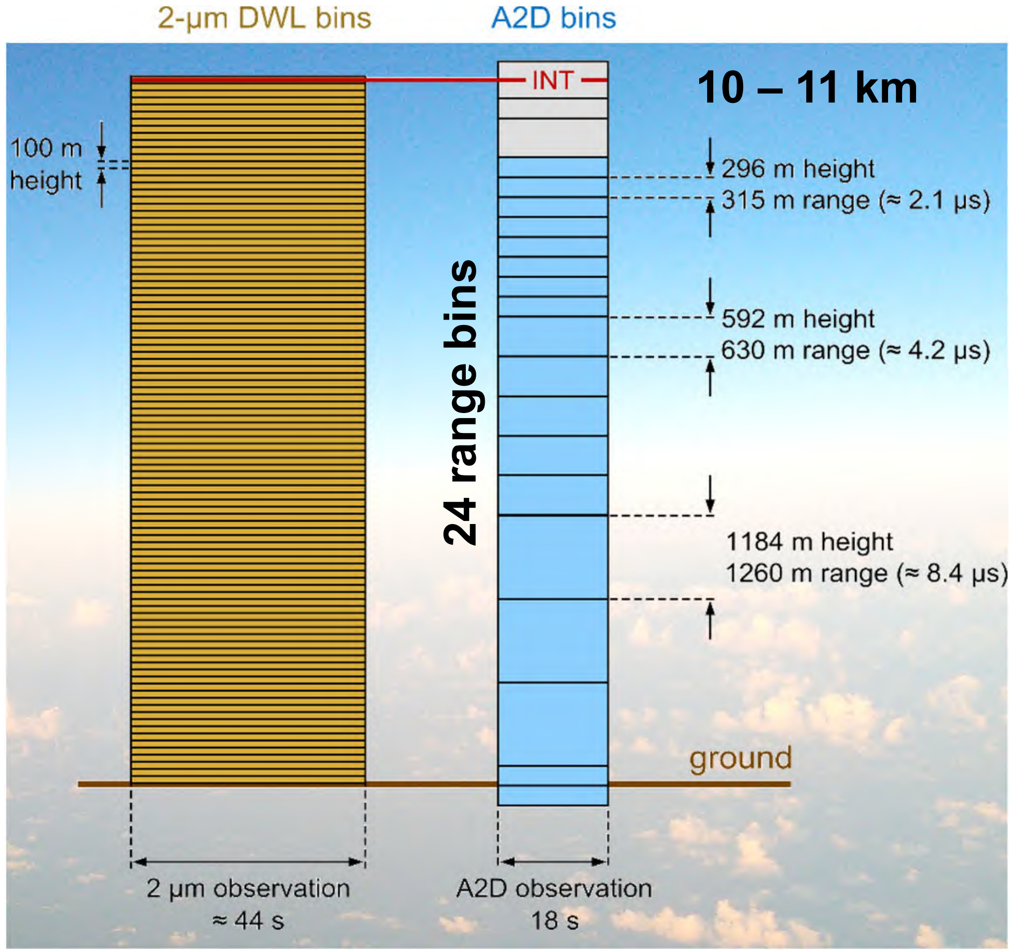


Reitebuch et al. (2009), **JAOT**; Lemmerz et al. (2017), **Applied Optics**, Lux et al. (2018), **AMT**, Marksteiner et al. (2018), **Remote Sensing**, Witschas et al. (2017), **JAOT**, Witschas et al. (2020), **AMT**, Lux et al. (2022a), **AMT**

See also ➔ **"The Relevance of Airborne Technology Demonstration for the Success of Aeolus and Aeolus-2"** @ Aeolus 3rd Anniv. Conference 2022

- The **A2D (ALADIN Airborne Demonstrator)** was built with a focus on high technological **commonality with the Aeolus lidar** (ALADIN), based on its Pre-Development Model spectrometers, detectors and a similar laser system, all engineered for airborne operations
- **A2D was operated** for measurements from ground and on the DLR Falcon 20 aircraft **together with the scanning heterodyne-detection *2-µm DWL*** which provided reference profiles of **wind speed and direction**
- Both DWLs were deployed to **validate the ALADIN concept** before launch with atmospheric signal, and to derive conclusions for retrieval algorithms ➔ **several ground and airborne campaigns <u>in the years before launch</u> supported preparing the Aeolus mission**

Parameter	DLR A2D	DLR 2-µm DWL
Wavelength	354.89 nm	2022.54 nm
Laser energy	50-60 mJ	1-2 mJ
Pulse repetition rate	50 Hz	500 Hz
Pulse length	20 ns (FWHM)	400-500 ns (FWHM)
Telescope diameter	20 cm	10.8 cm
Vertical resolution	300 m to 2.4 km	100 m
Temporal averaging raw data (horizontal)	20 shots = 400 ms	single shot = 2 ms
Temporal averaging product (horizontal)	14 s (+4 s data gap)	1 s per LOS (500 shots), 44 s scan (21 LOS)
Horizontal resolution @ 200 m·s^{-1} = 720 km/h = 12 km/min.	3.6 km (18 s)	0.2 km LOS, 8.4 km scan
Precision (random error)	1.5 m·s^{-1} (Mie) 1.8 m·s^{-1} (Rayleigh)	< 1 m·s^{-1}

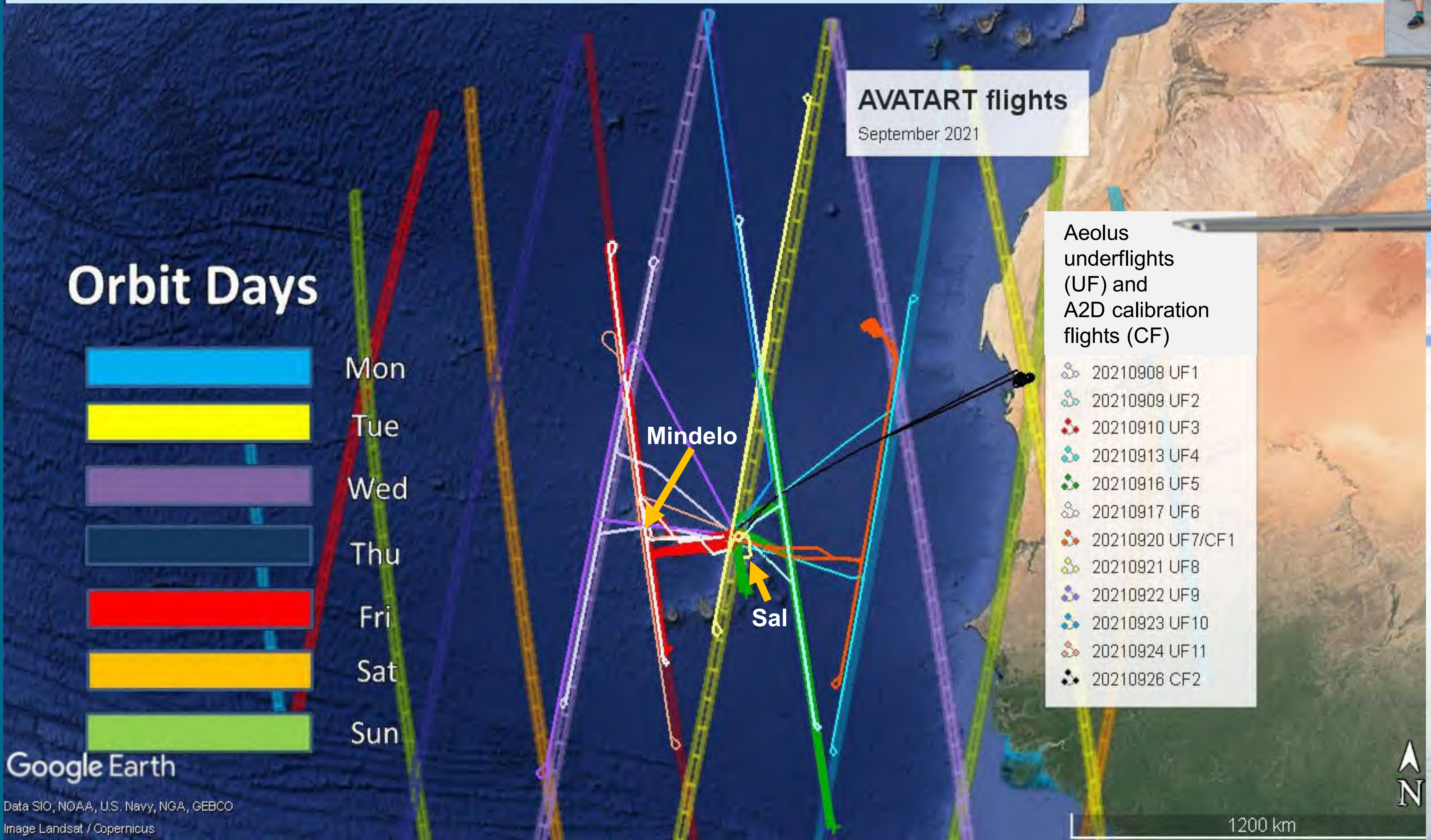


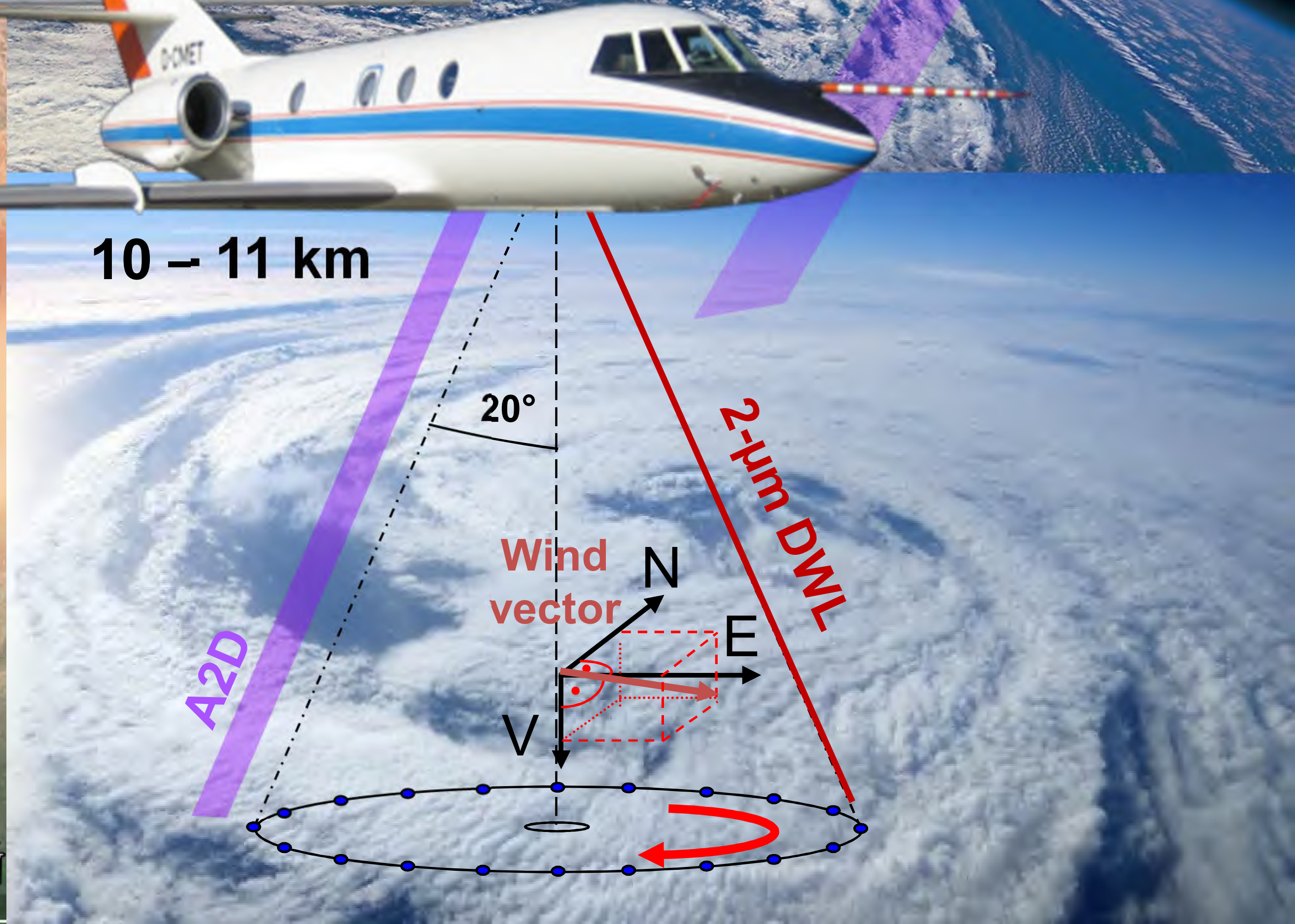
Aeolus Airborne Validation Goals

➔ **Characterization of the Aeolus wind products with parallel collocated measurements along the Aeolus track** (wind, clouds, aerosol information with higher accuracy/precision and vert./hor. resolution)

➔ **Results for the processor evolution, validation of reprocessed data, and the Cal/Val community**

Aeolus tracks within reach of the Falcon from Sal and underflights performed during AVATAR-T/JATAC 21





Aeolus Airborne Validation Campaigns After Launch

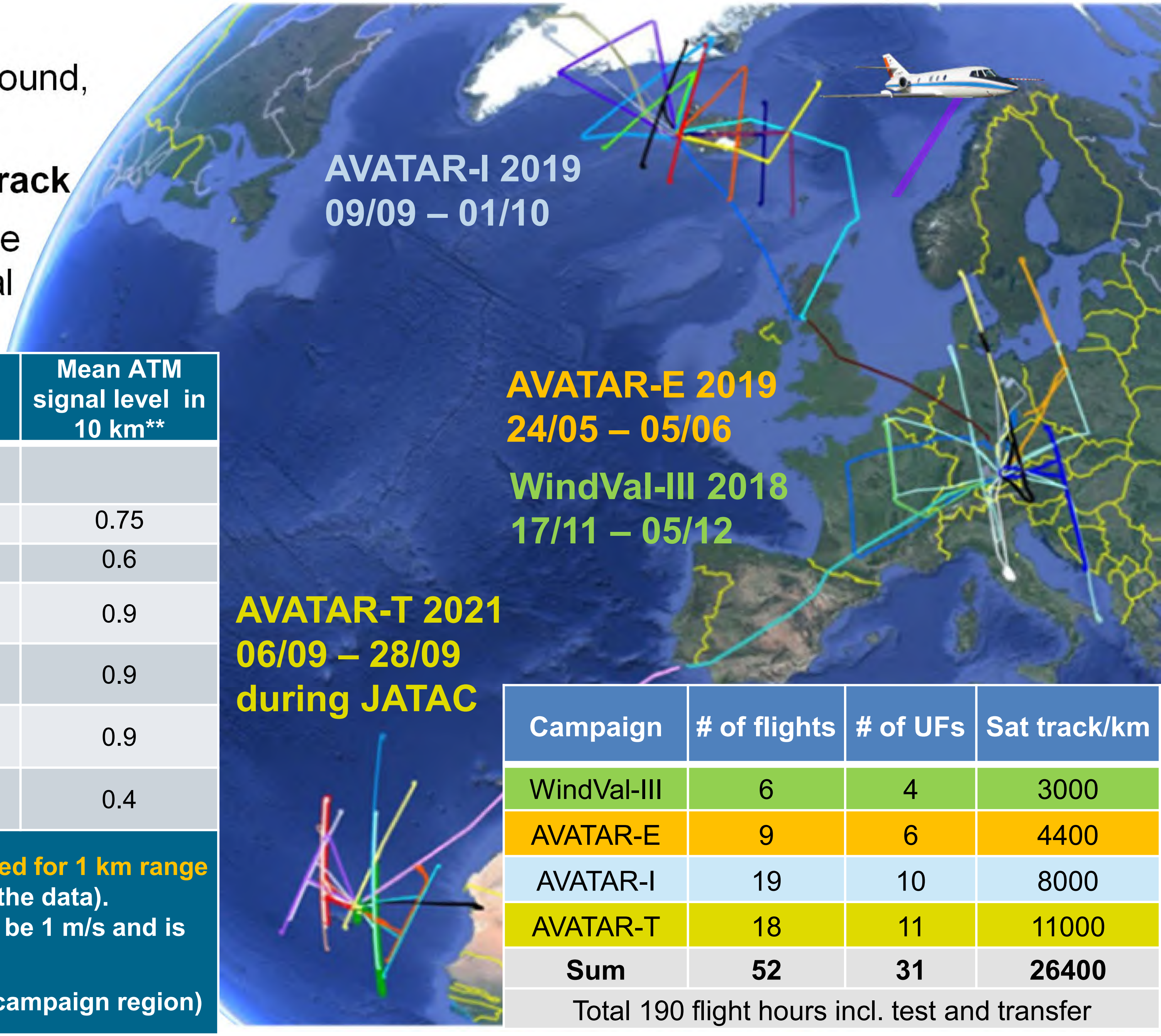
4 airborne campaigns were performed…

- ✓ **under different conditions** (Aeolus signal, solar background, atmospheric dynamics, geographical regions)
- ✓ with a **total of 52 flights, 26400 km along the Aeolus track**
- ✓ providing **high resolution and high quality data** with the intermediate perspective between ground- and Numerical Weather Prediction - based validation

Campaign/data set (NRT baseline)	Systematic error/(m/s)*		Random error (scaled MAD)/(m/s)*		Mean laser energy PD 74/(mJ)	Mean ATM signal level in 10 km**
	Rayleigh	Mie	Rayleigh	Mie		
WindVal III (B2)	2.1	2.3	4.0/3.9	2.2/2.0	53	0.75
AVATARE (B3)	-4.6	-0.2	4.4/4.3	2.2/2.0	42	0.6
AVATARI (asc., B6)	0.0	-0.2	4.3/4.2	2.8/2.7	62	0.9
AVATARI (desc., B6)	1.8	-0.6	3.9/3.8	2.5/2.3	62	0.9
AVATARI (2nd repro. B11, L2bP 3.40)	-0.8	-0.9	3.9/3.8	2.7/2.5	62	0.9
AVATART (B12 NRT L2bP 3.50)	-0.1	-0.7	6.1/6.1	2.9/2.7	72	0.4

* For better comparison between campaigns, Rayleigh random errors are calculated for 1 km range bins assuming Poisson noise (AVATART 750 m range gates contributed ~75% of the data). Systematic error of the 2-µm DWL is neglected, the random error is considered to be 1 m/s and is corrected (value on the right side of the slash)

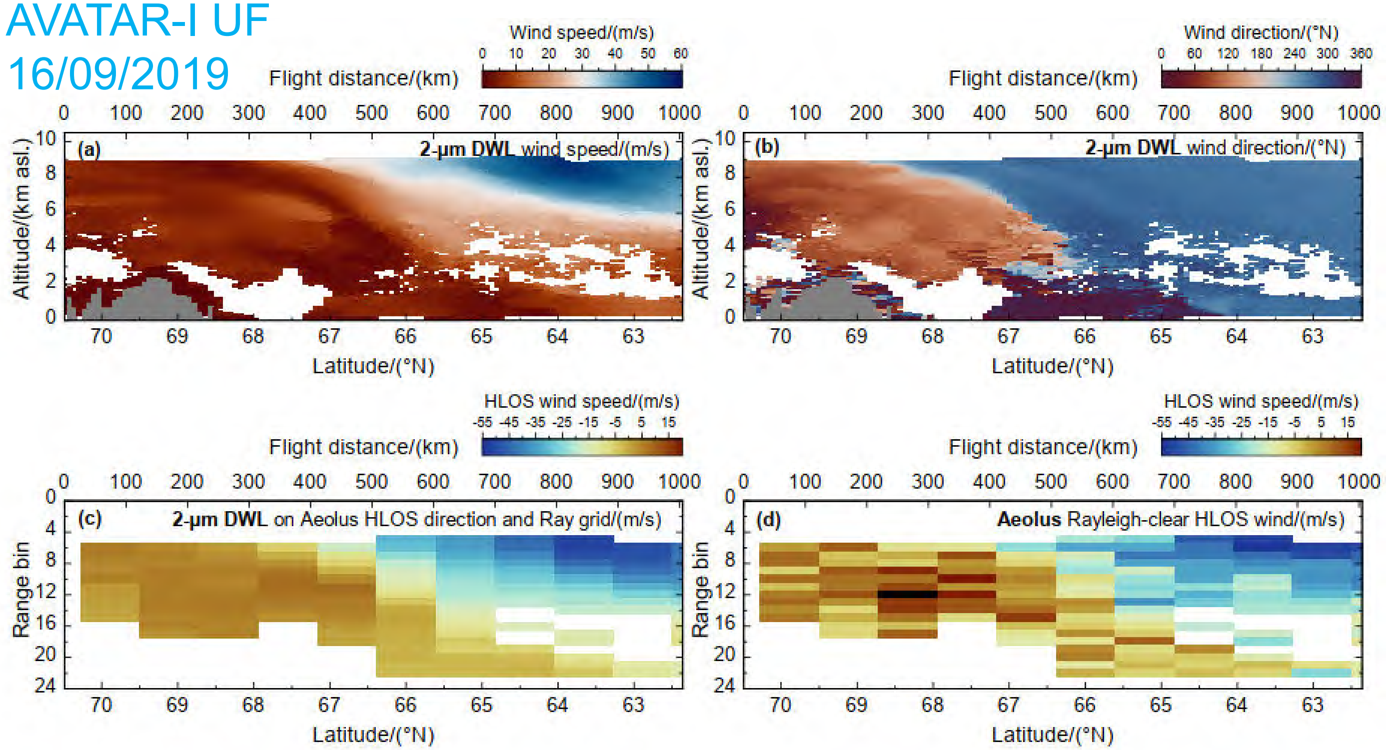
** ATM signal is given in arb. units and as a mean per orbit (not for the particular campaign region)

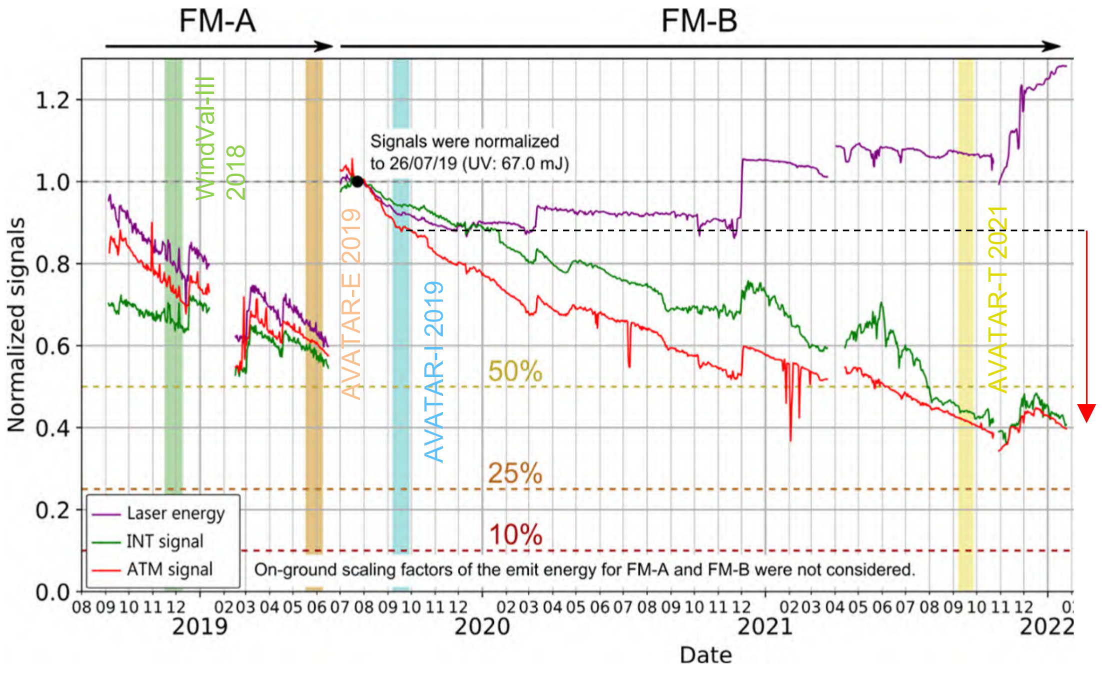


Campaign	# of flights	# of UFs	Sat track/km
WindVal-III	6	4	3000
AVATAR-E	9	6	4400
AVATAR-I	19	10	8000
AVATAR-T	18	11	11000
Sum	**52**	**31**	**26400**
Total 190 flight hours incl. test and transfer			

Statistical Comparison of Aeolus and 2-µm DWL Wind Data

AVATAR-I UF
16/09/2019



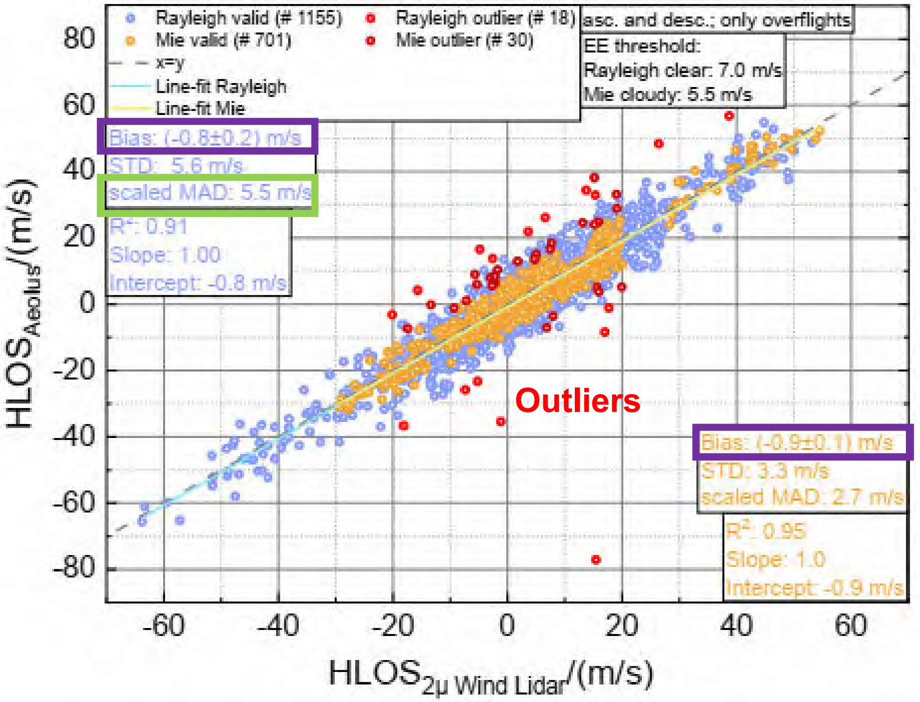


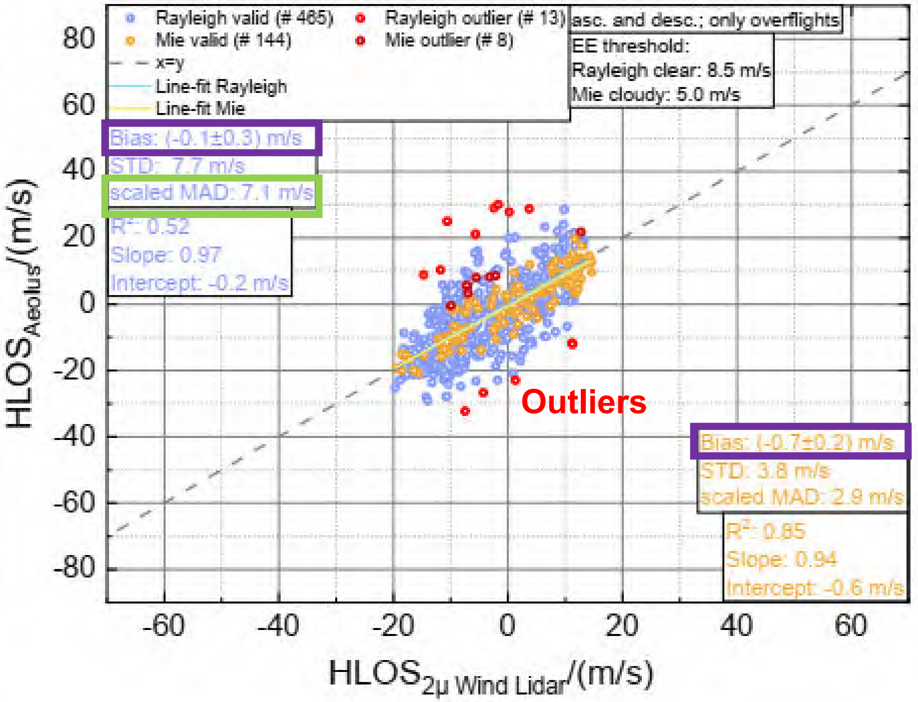
Aeolus
signal evolution

AVATAR-I (2019)

Mie-cloudy
Rayleigh-clear

AVATAR-T (2021)

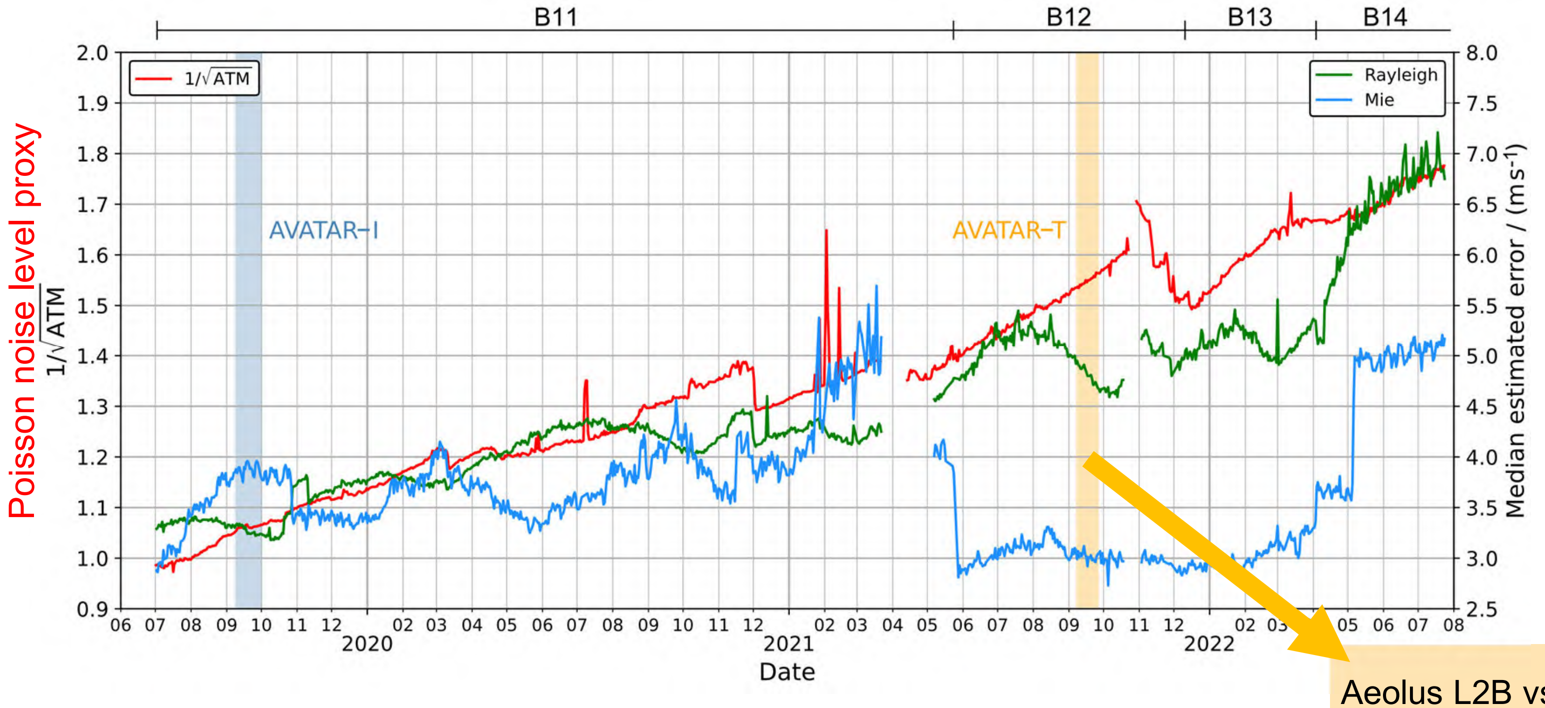




- Multiple Aeolus underflights are necessary to obtain robust statistics
- **Systematic errors of Rayleigh and Mie winds are close to the mission requirement** (<0.7 m/s)
- **Rayleigh random error has significantly increased between 2019 and 2021** from 5.5 m/s (B11) to 7.1 m/s (B12) due to the signal loss, partly mitigated by the smaller solar background in the tropics

→ ***Witschas et al., AMT (2022)***

Influence of QC 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*

Quality Control (QC) scheme based on a combination of the EE and the modified Z score (Z_m) is necessary for comparable validation results and compliance with the error definitions of the Aeolus mission requirements doc.:

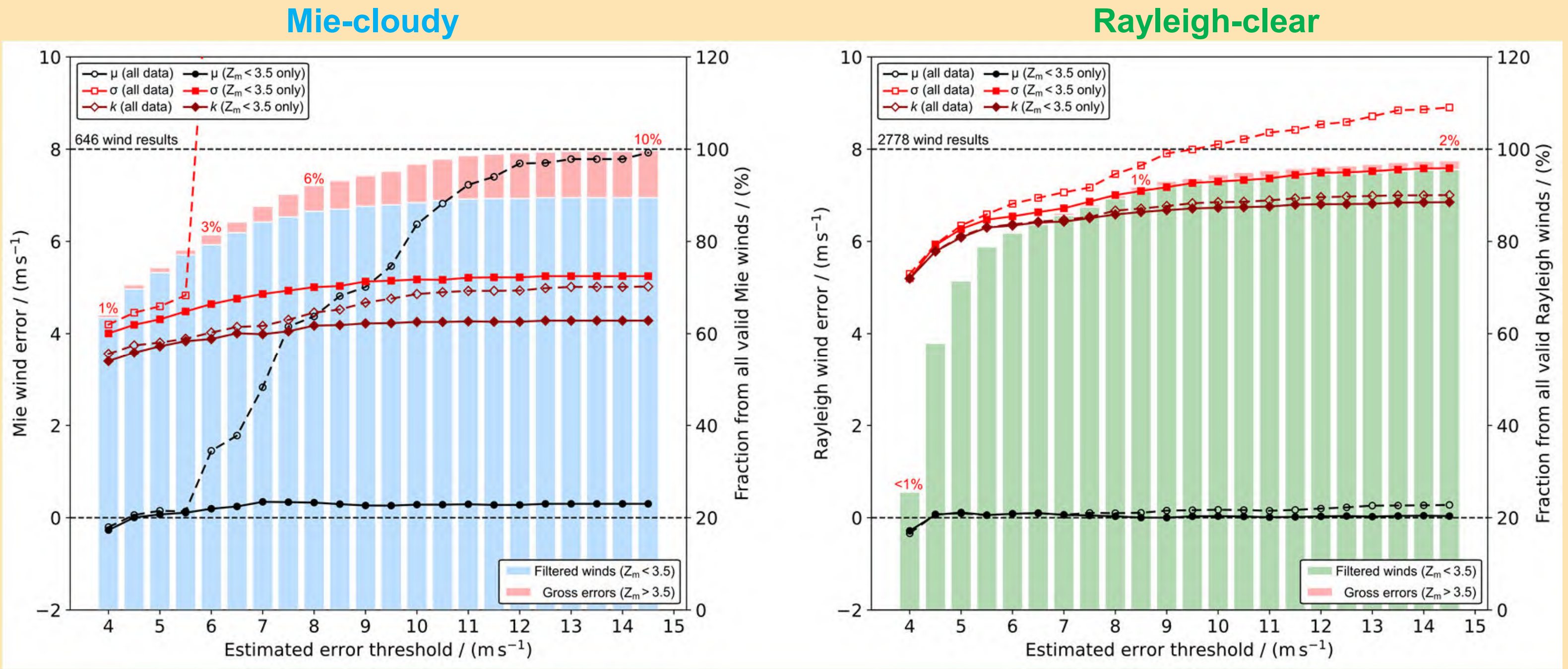
➔ **careful statistical analysis**

➔ **rigorous screening for outliers**

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

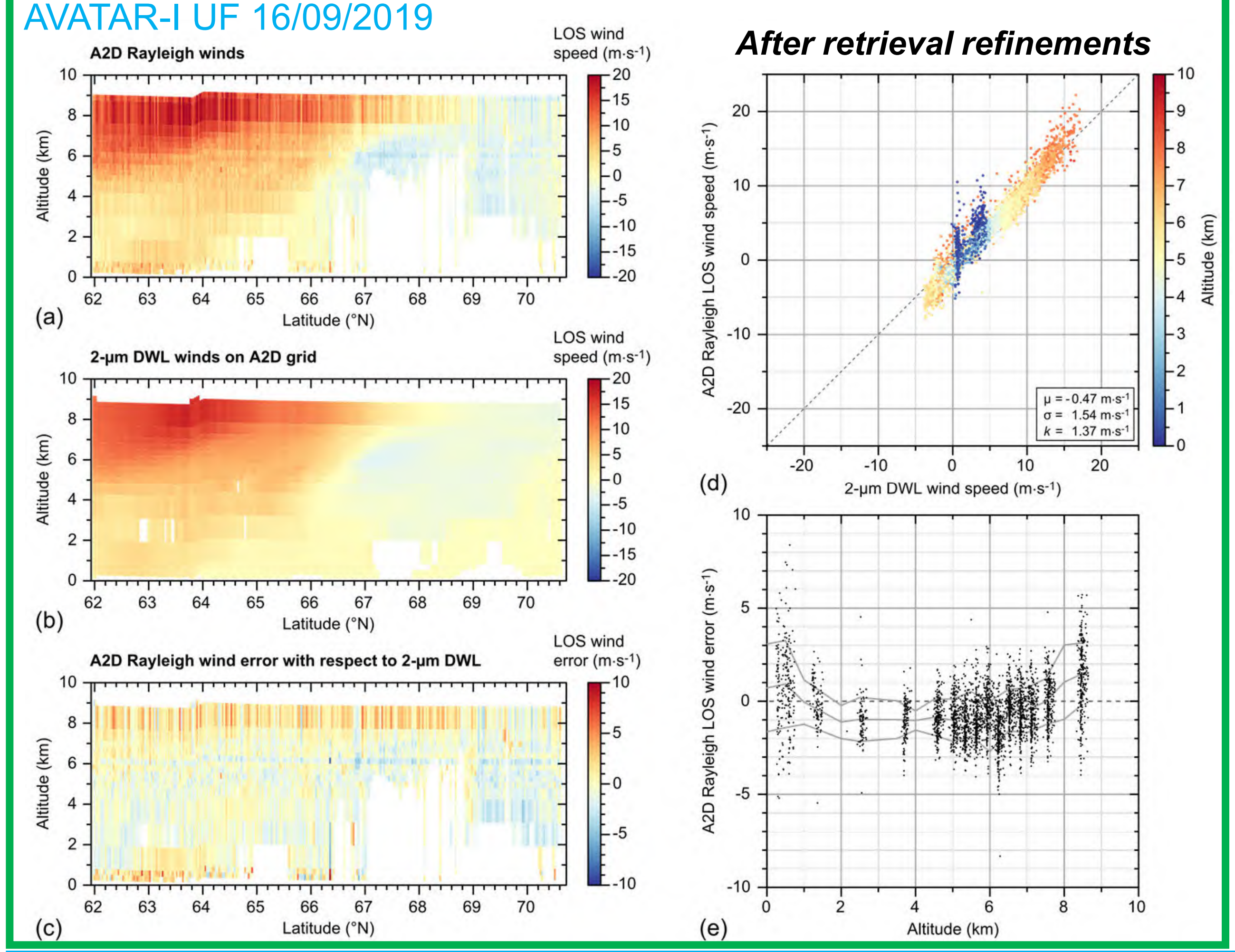
See Lux et al., AMT (2022b) and e.g. Kirkwood et al., AMTD (2023)

Aeolus L2B vs. ECMWF model background winds → QC dependence on error statistics for **AVATAR-T** flights



Improvements of the A2D Wind Retrieval Algorithm

AVATAR-I UF 16/09/2019

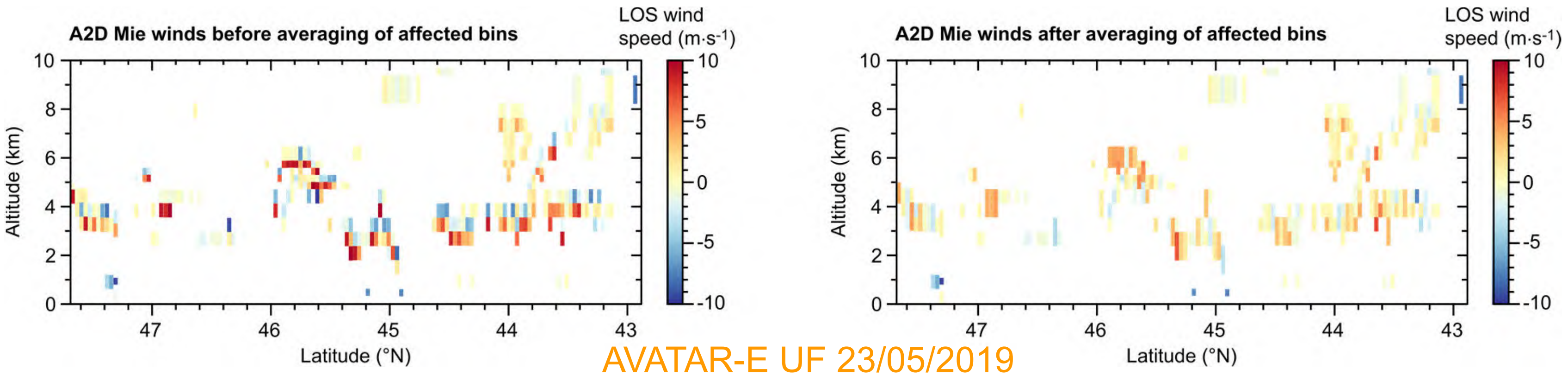


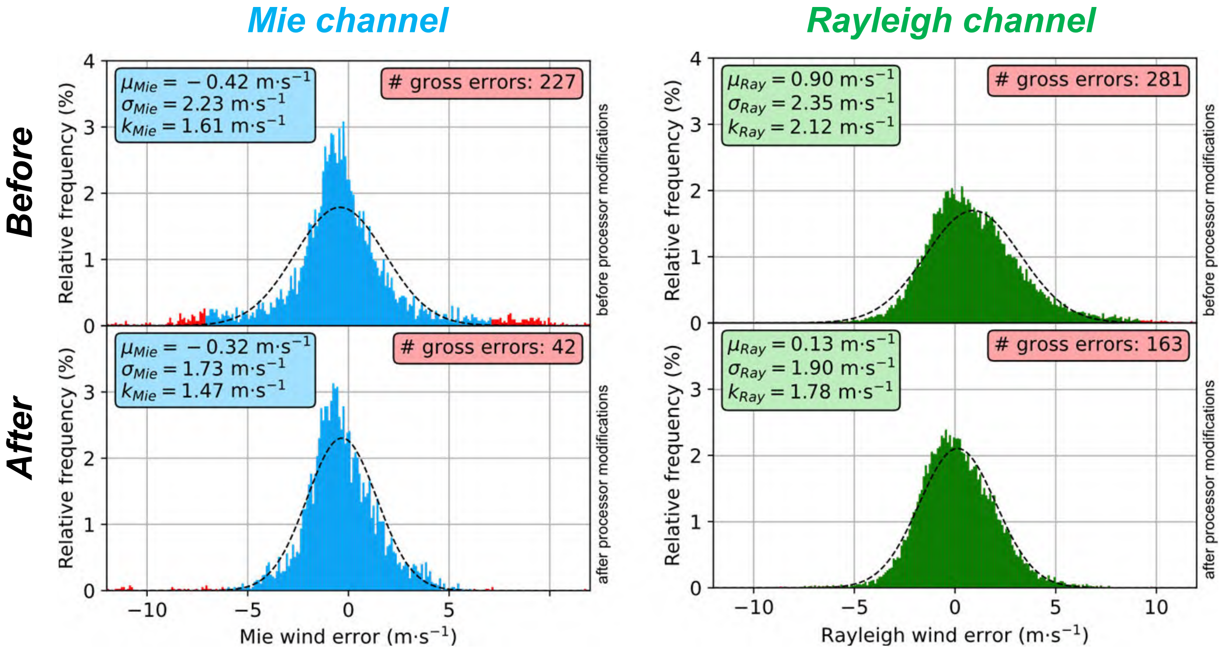
- Implementation of a **new QC based on Rayleigh spot positions** to filter out poor alignment on measurement level

→ **Relevant for potential Aeolus spot position dependent Rayleigh response corrections and Aeolus-2 (bi-static design as A2D)**

- Extension of "high quality" measurement range closer to the aircraft from ~8 km to ~10 km altitude
- **Bin averaging in regions with large backscatter gradients** to mitigate the detrimental influence of Mie fringe skewness

→ **Substantial reduction of the random error of both channels from more than 2.0 m/s to ~1.5 m/s (LOS)**



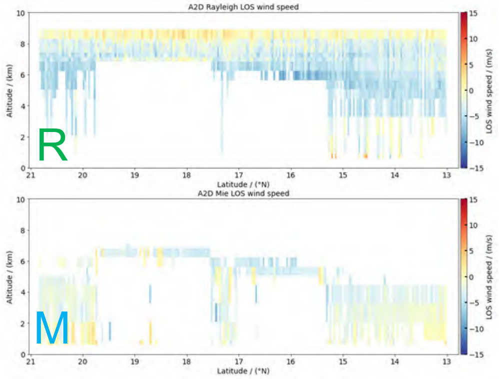


Example: Improvements for AVATAR-I campaign data

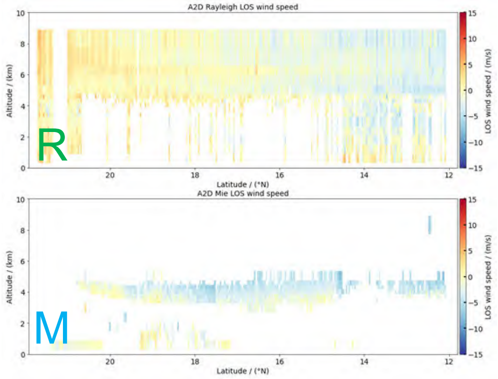
→ ***Lux et al., AMT (2022a)***

A2D Rayleigh and Mie Wind Data of the 11 AVATAR-T Underflight Legs

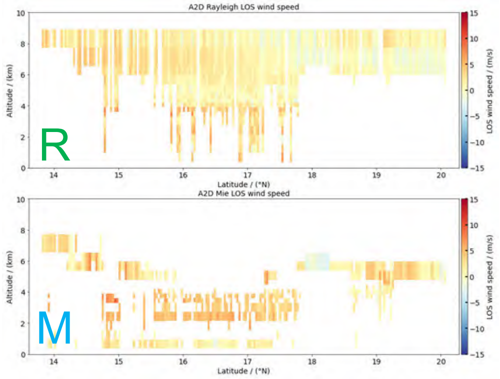
8 September 2021



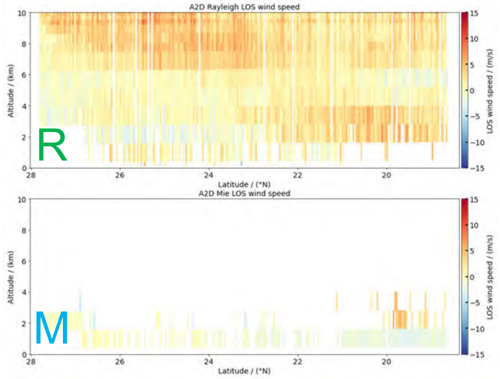
13 September 2021



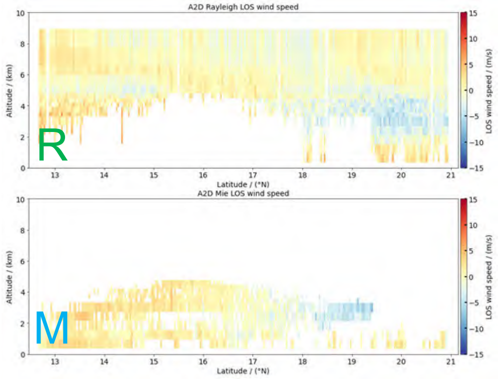
20 September 2021



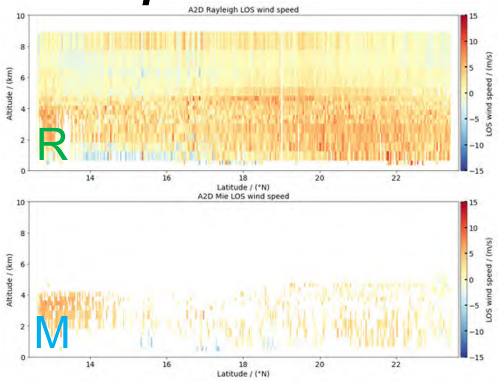
23 September 2021



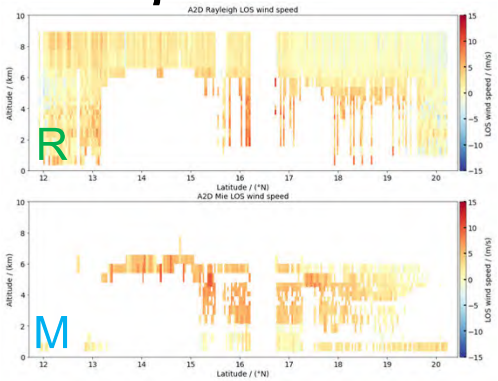
24 September 2021



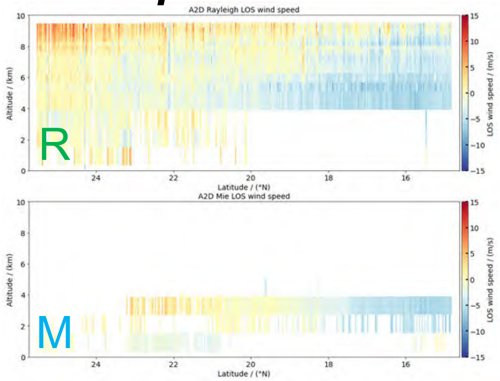
9 September 2021



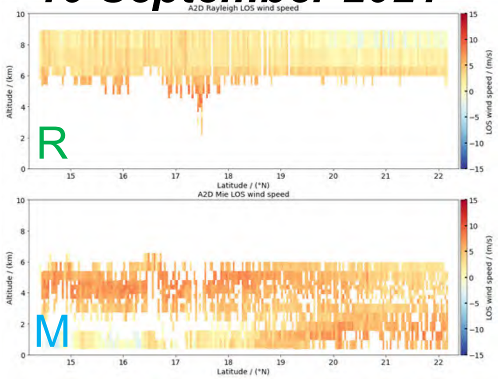
16 September 2021



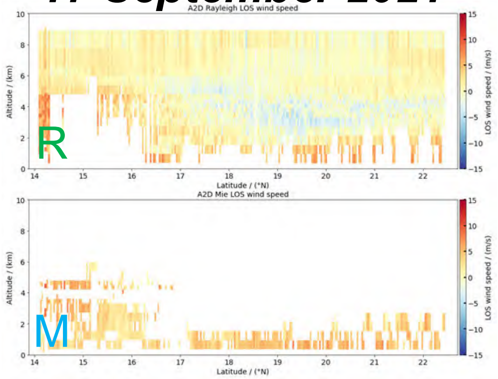
21 September 2021



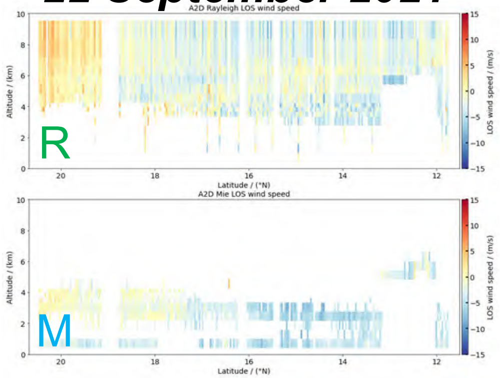
10 September 2021



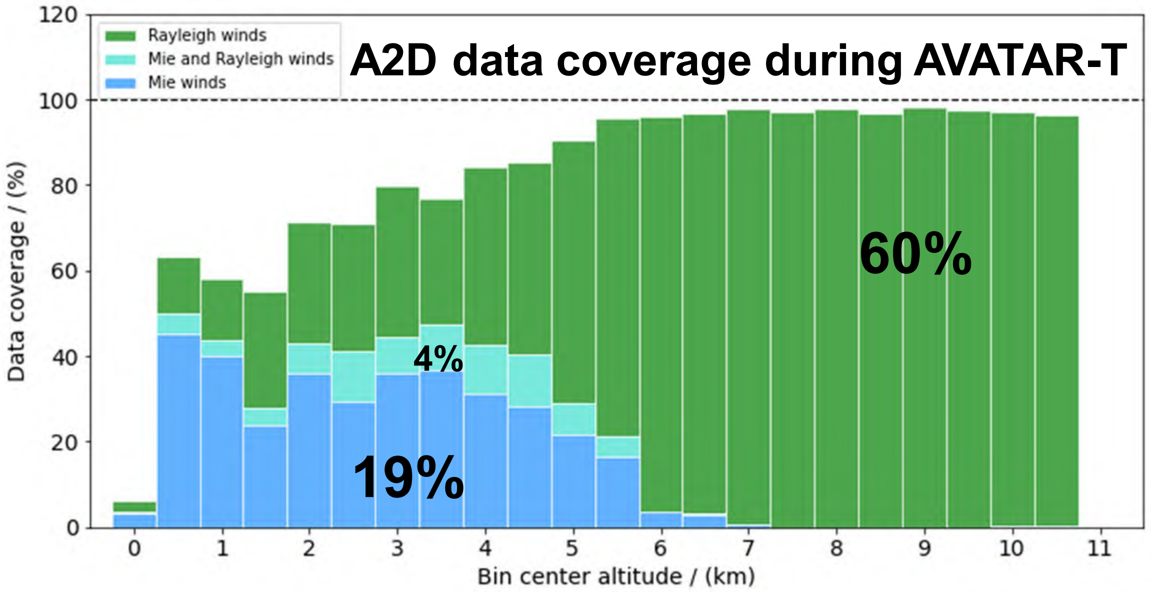
17 September 2021



22 September 2021



- Rayleigh winds are obtained from clear sky above clouds and SAL; Mie winds are collected from cloud and aerosol backscatter
- Low wind speeds (<10 m/s LOS ≈ 30 m/s HLOS)



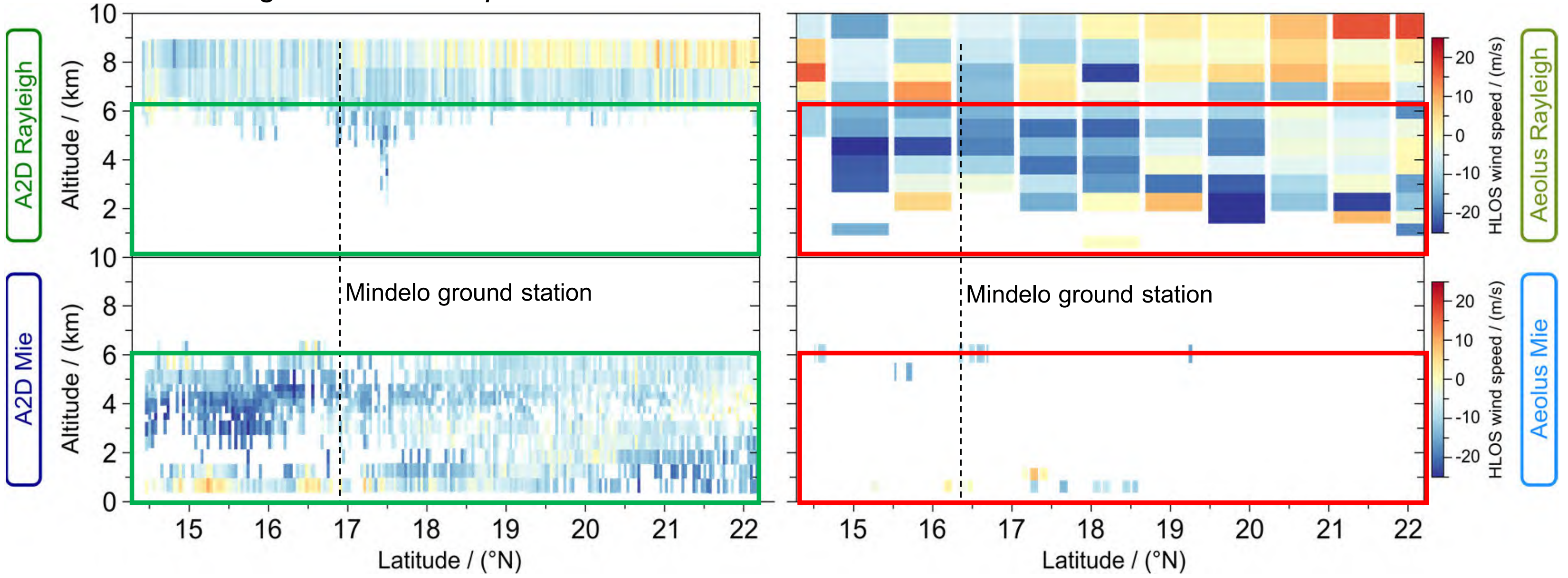
Current Data Analysis and Algorithm Developments

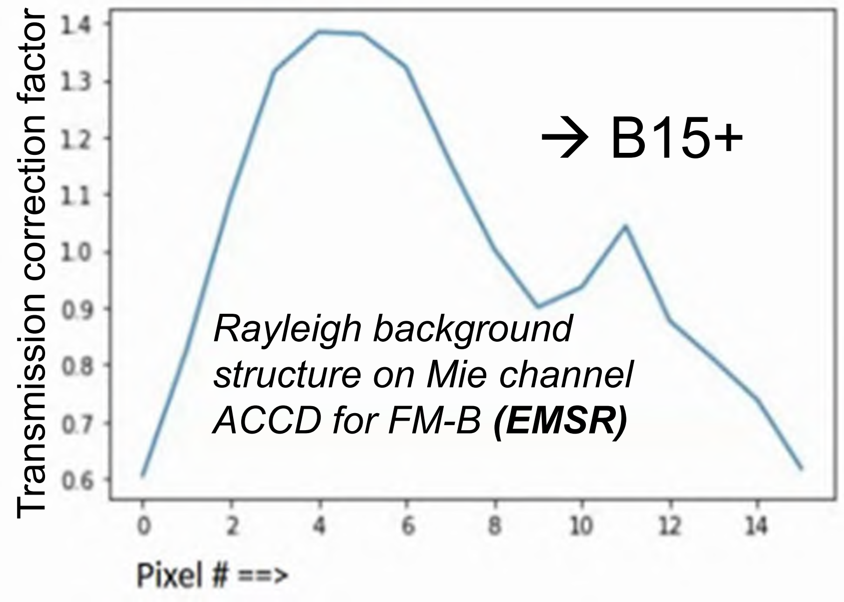
Study topics based on FM-B campaign data AVATAR-I/T:

- Very low Aeolus Mie-cloudy data coverage compared to A2D (and 2-µm DWL) in the dust-laden altitudes up to 6 km
- Refinement of Mie core algorithm by using a Pseudo-Voigt fit or a contrast function for the fringe analysis → ***poster by B. Witschas***
- Improved background correction for L2A SR as similarly implemented for A2D Mie winds (adoption of Effective Mie Spectrometer Response, EMSR, for Mie winds)
  → ***presentation by P. Wang*** *(KNMI), Wednesd.*
- Investigation of the Rayleigh-clear wind error depending on the scattering ratio

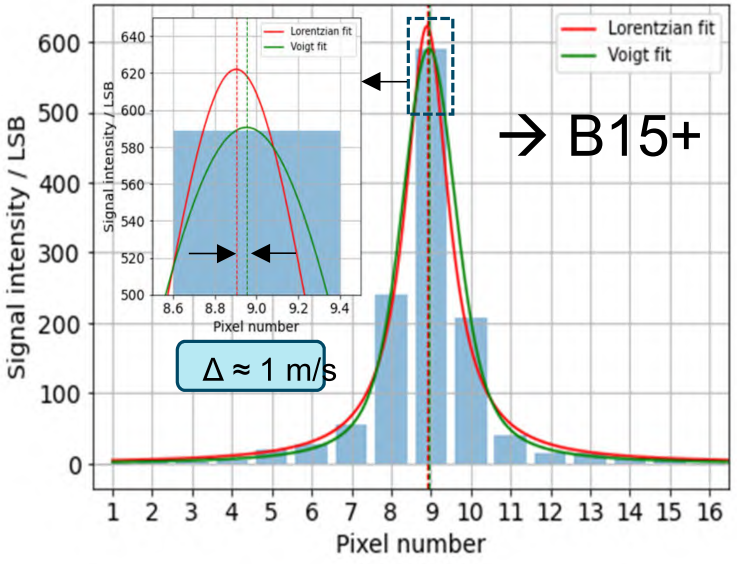
➢ ***Goals: Improvement of scattering ratio in the L1B product and exploration of the potential to get more good-quality Mie winds in aerosol regions***

Wind data from Aeolus and A2D Rayleigh and Mie channels from Friday evening ascending orbit on 10 September 2021 AVATAR-T UF





Credits: D. Donavan, P. Wang (KNMI)

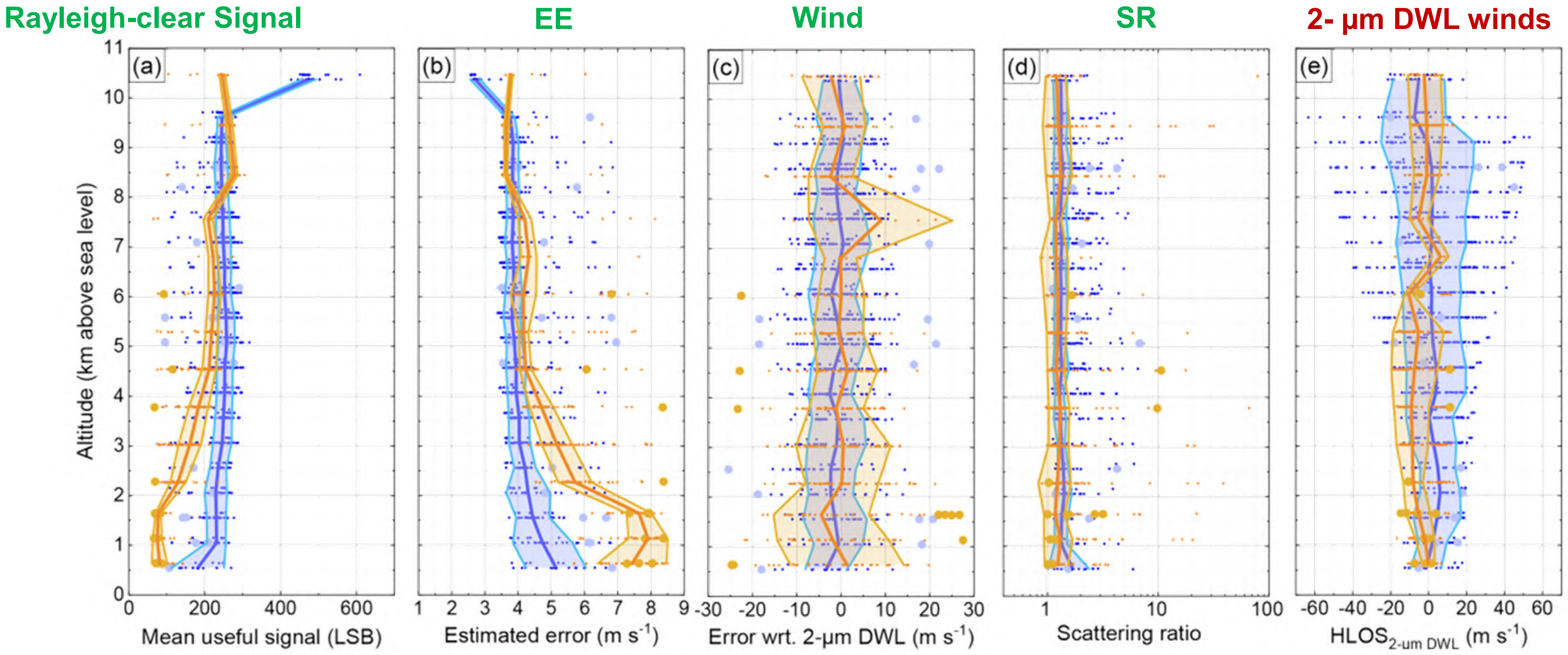


Lorentzian and Voigt fits of the Mie fringe

Aeolus data altitude dependence comparison AVATAR-I/T

DLR

- Compared to AVATAR-I (B11) the AVATAR-T (B12) campaign data shows **increased Aeolus Rayleigh-clear random errors** due to the **lower signal** at the time and the **strong attenuation in the dust layer**
- There is **no clear sign for an altitude dependent bias** during both campaigns

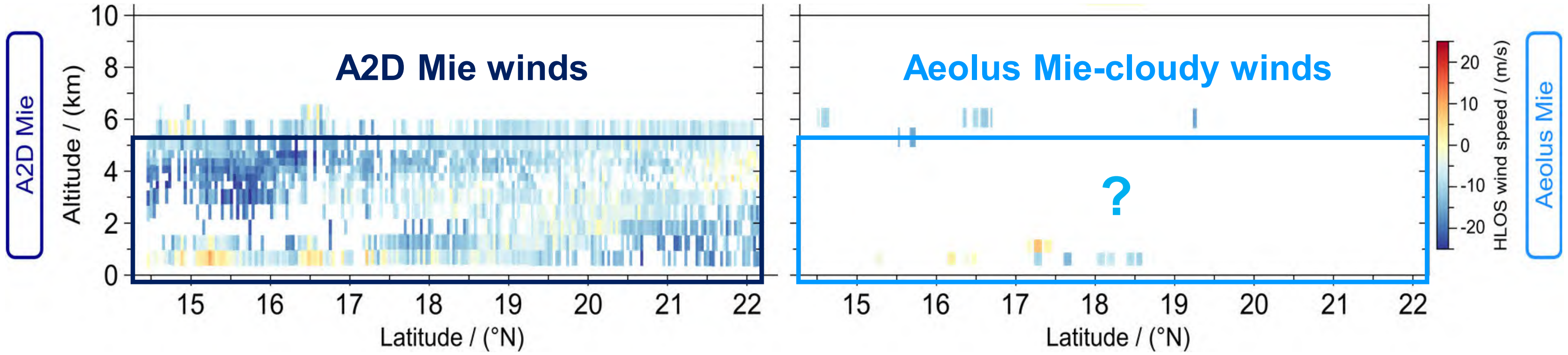


The actual valid data set (B11/B12) is indicated by the small points; the outliers defined by the modified *Z*-score threshold of 3 are plotted by larger dots. The median value per each range gate is indicated by the solid line, and the shaded area indicates the median plus–minus the scaled MAD for each range gate. ➔ ***Witschas et al., AMT (2022)***

Impact of processor updates on the Mie-cloudy winds

- **Lack of Aeolus Mie-cloudy winds compared to A2D coverage in Saharan Air Layer (AVATAR-T)**

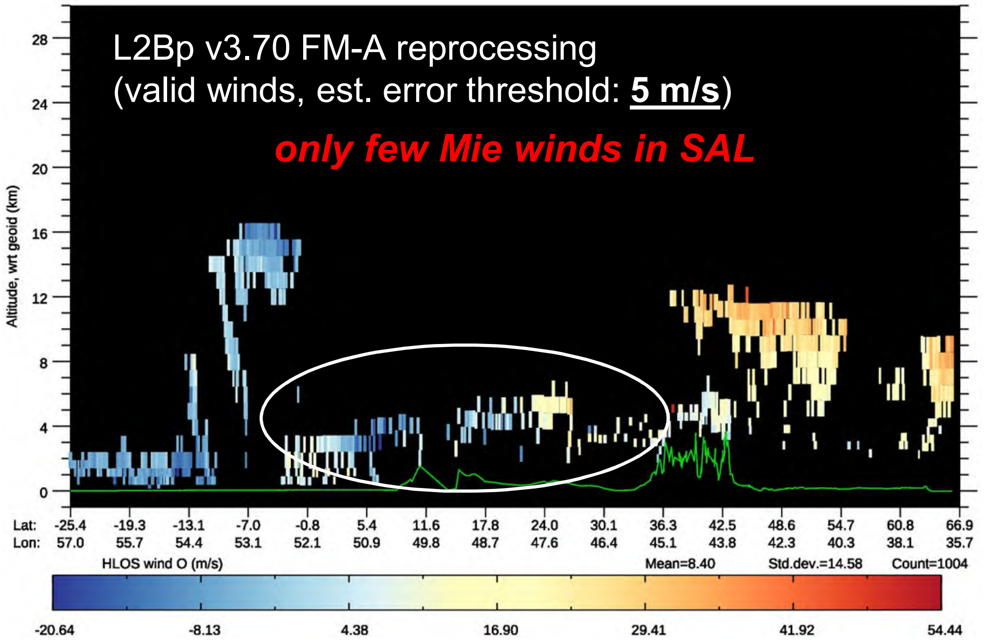
Wind data from Aeolus and A2D Rayleigh and Mie channels from the Aeolus underflight on 10/09/2021



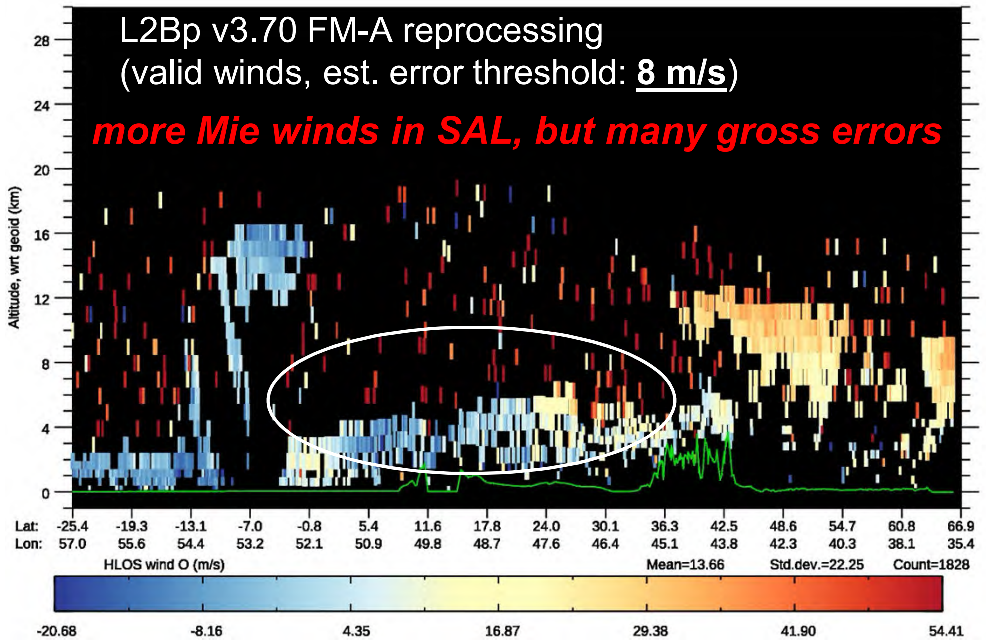
- ✓ Implementation of a **"residual error" threshold for QC of Mie Core output and improved correction for the Rayleigh background** (EMSR) on the Mie channel increases the Mie data coverage, as it allows to relax the estimated error threshold
- ✓ **New QC scheme was optimized for a test case in the 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 results from 1 May 2019 (B15** ECMWF study by Mike Rennie)

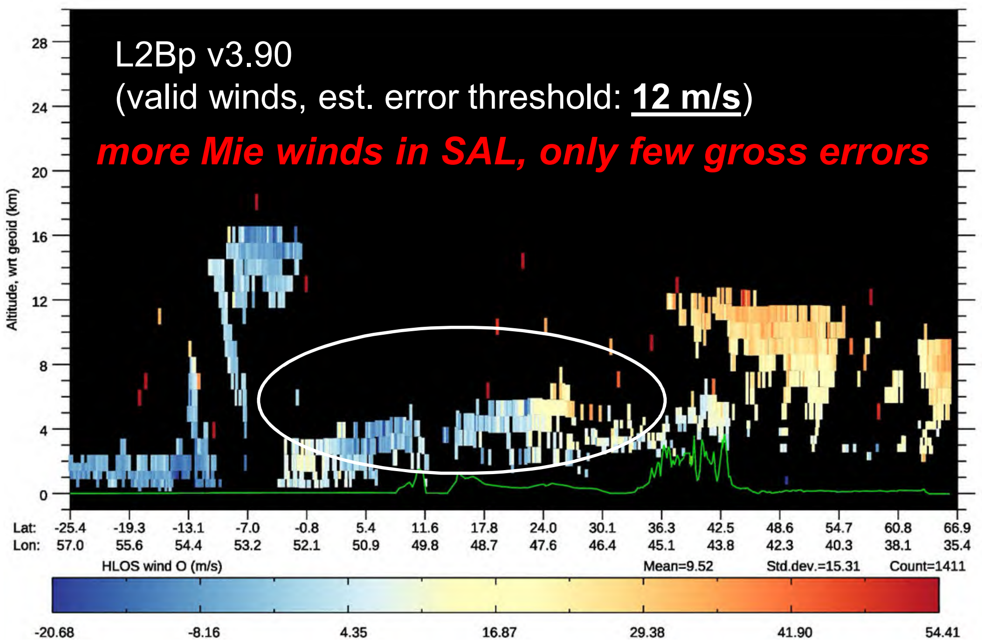
***Before** processor updates, EE < 5 m/s*



***Before** processor updates, EE < 8 m/s*



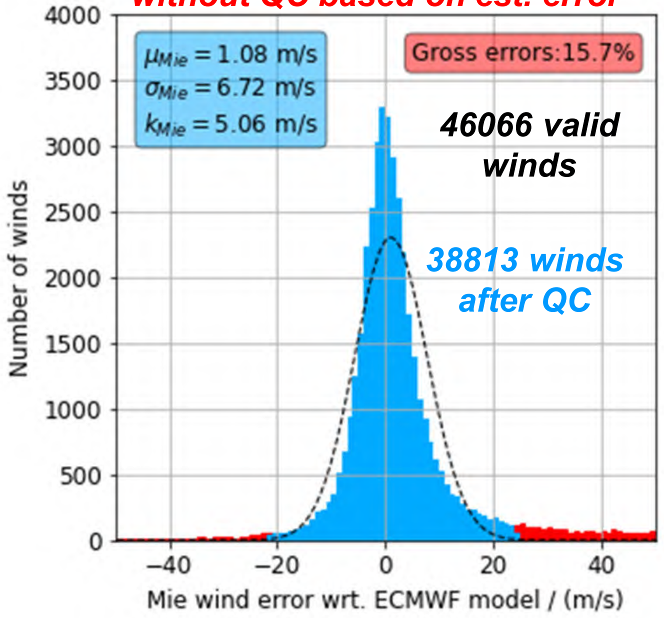
***After** processor updates, EE < 12 m/s*



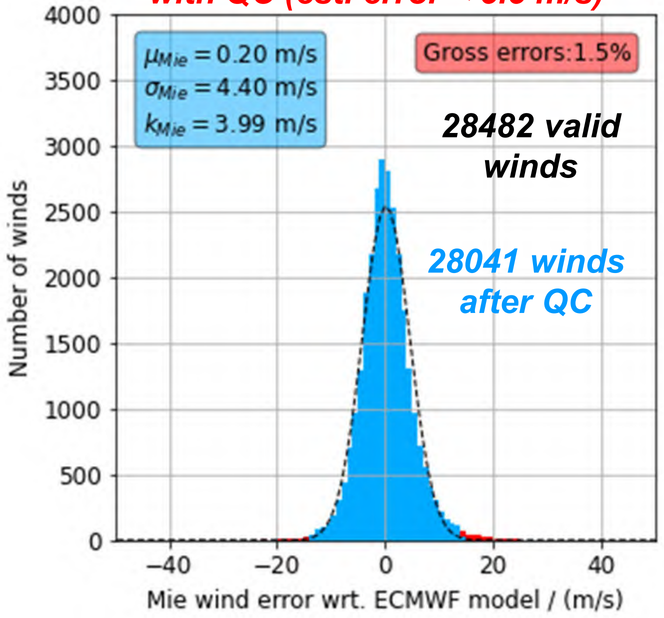
Improvement of the Mie wind data quality with B16*

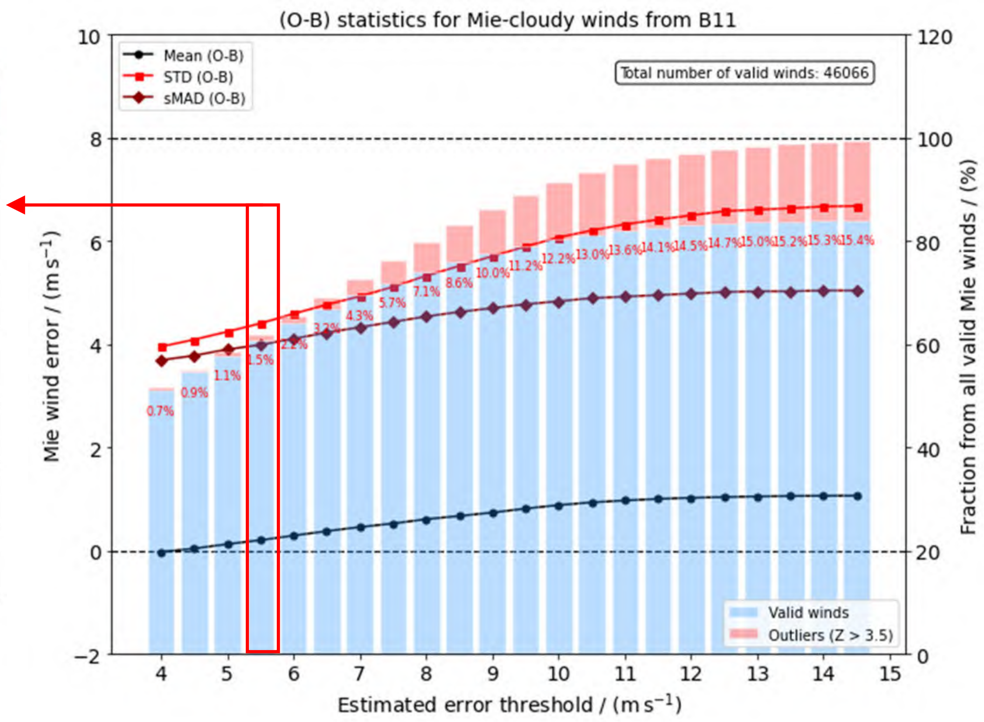
5 full orbits from AVATAR-I underflights in September 2019 before processor updates

without QC based on est. error

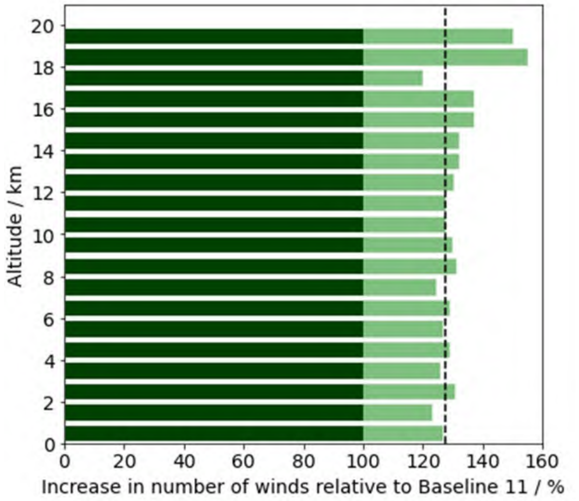


with QC (est. error < 5.5 m/s)

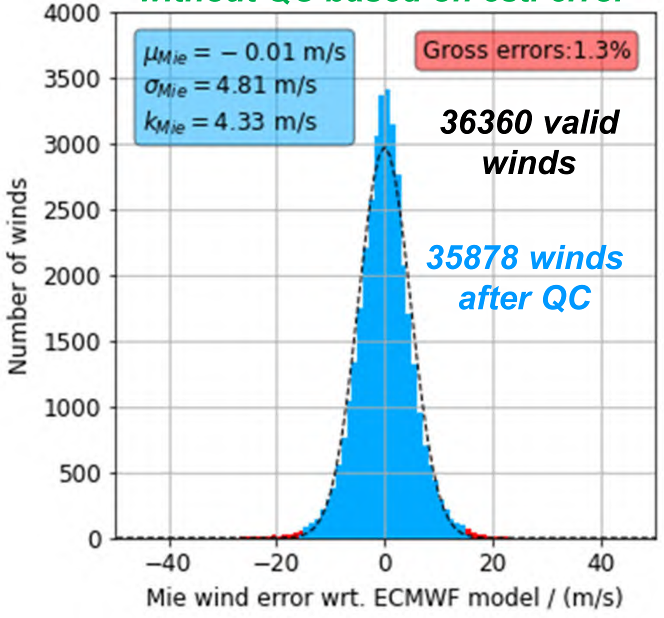


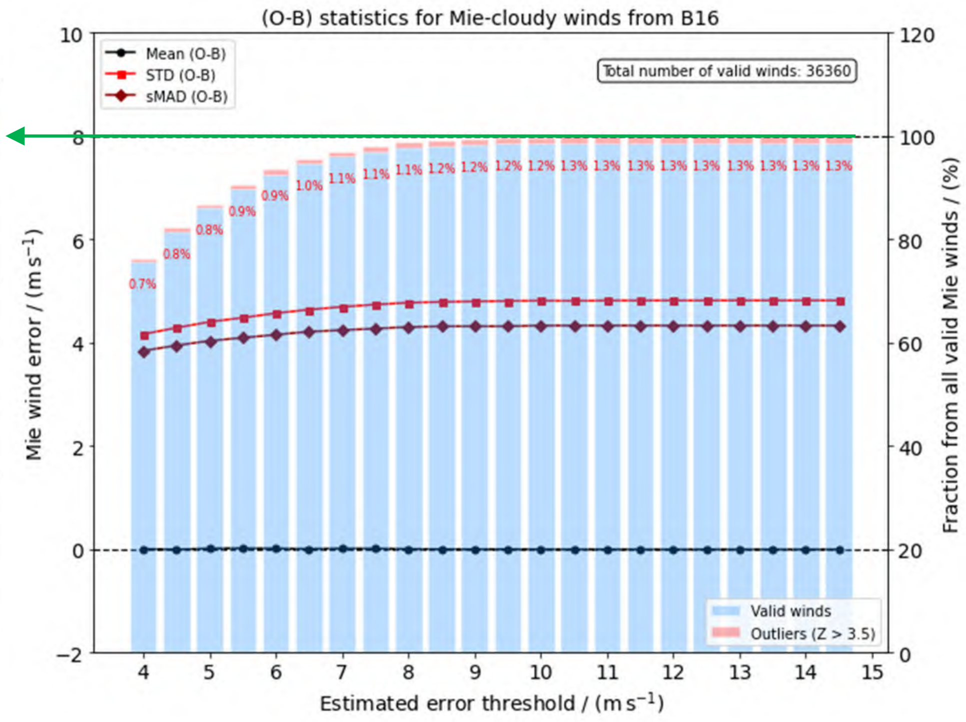


Increase in number of winds per altitude bin of 1 km



After processor updates without QC based on est. error

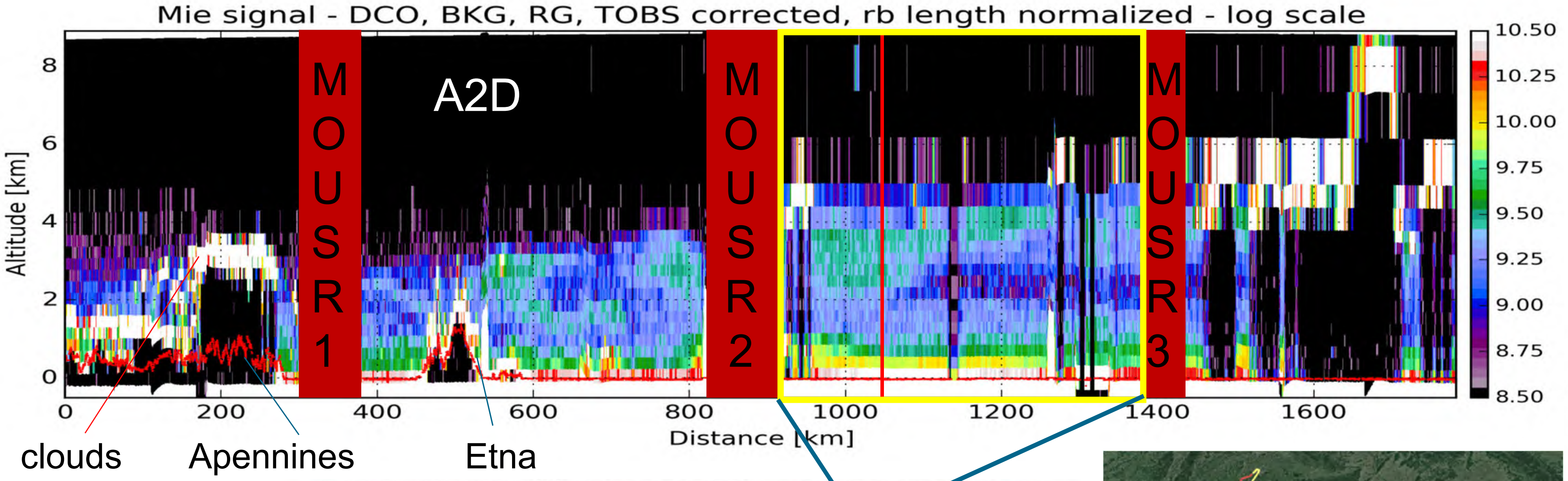


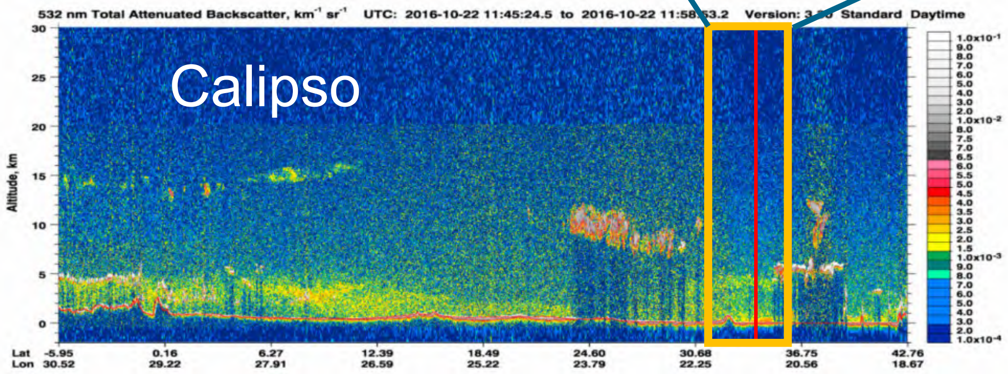


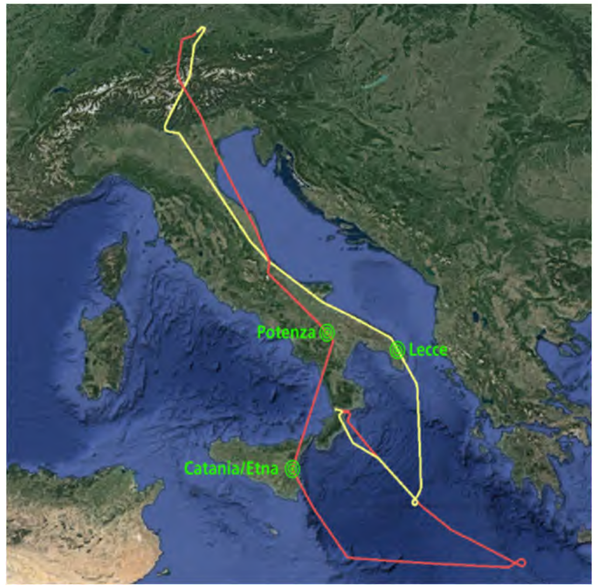
- Thanks to the processor updates, **gross errors are largely eliminated (<2%) for the Mie-cloudy winds even without applying an estimated error filter**.
- The **remaining few gross errors are evenly distributed**, hence the bias does not change depending on QC settings.
- The **random error is only 7% larger** (sMAD k ≈ 4.3 m/s compared to 4.0 m/s) **despite still *preliminary processing** for test cases (Mie response calibration, Mie nonlinearity, Rayleigh background array, M1 temp. correction not updated).
- 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.

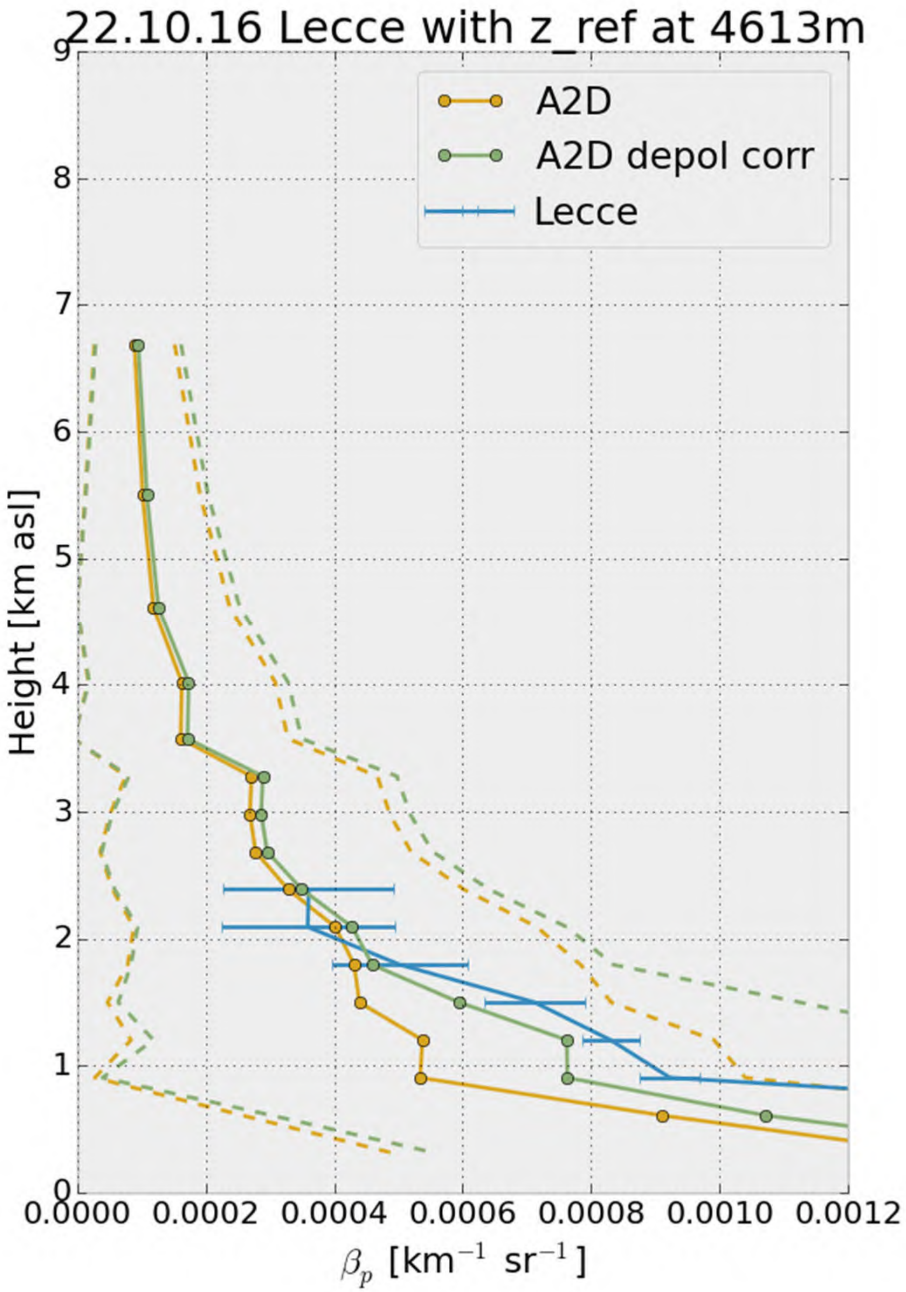
A2D Aerosol Retrieval Demonstrated in 2016

Aerosol flights on 22/10/2016 – A2D Mie signal









Red line marks the Calipso overpass region:
➔ Vertical aerosol extent is approximately in the same range as A2D has measured: top at ~5 km

Courtesy Alexander Geiß, ESA/ESTEC at the time, now LMU

- **In principle also A2D aerosol products could be derived for utilizing the airborne campaign data – sets also for L2A processor evolution**

Stratospheric aerosol from the CORAL lidar in South America

Rayleigh lidar

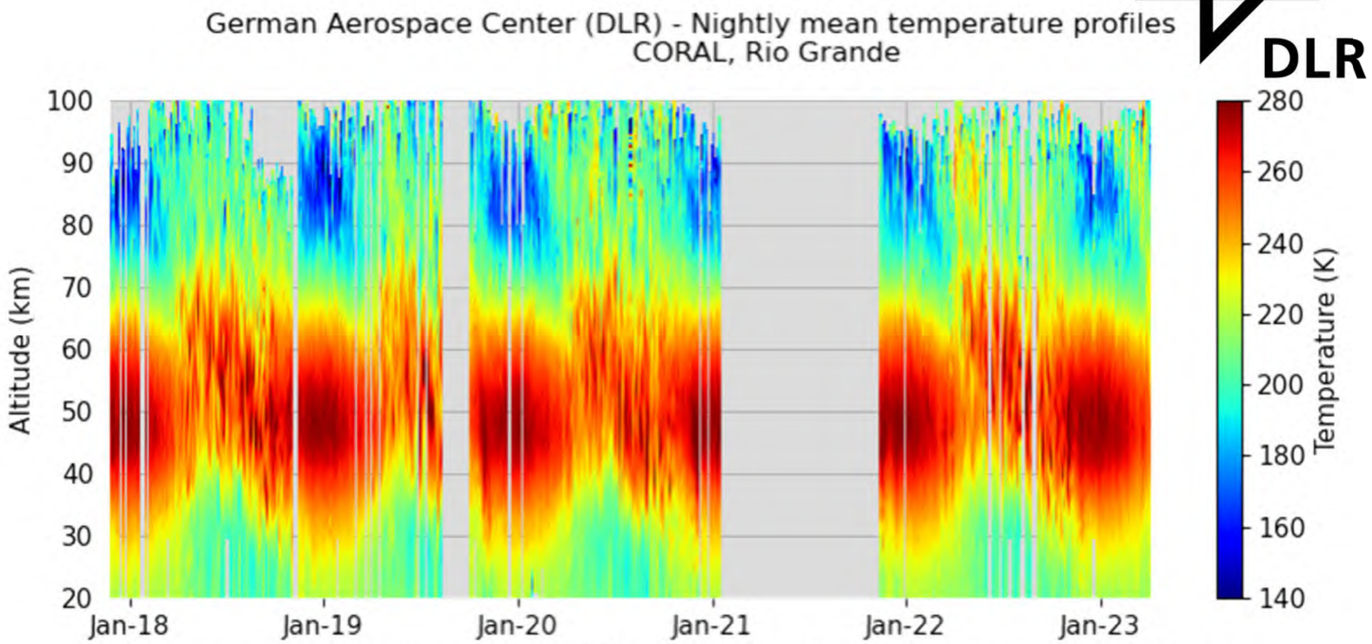
- 53.8S, 67.8W
- Rio Grande, Argentina

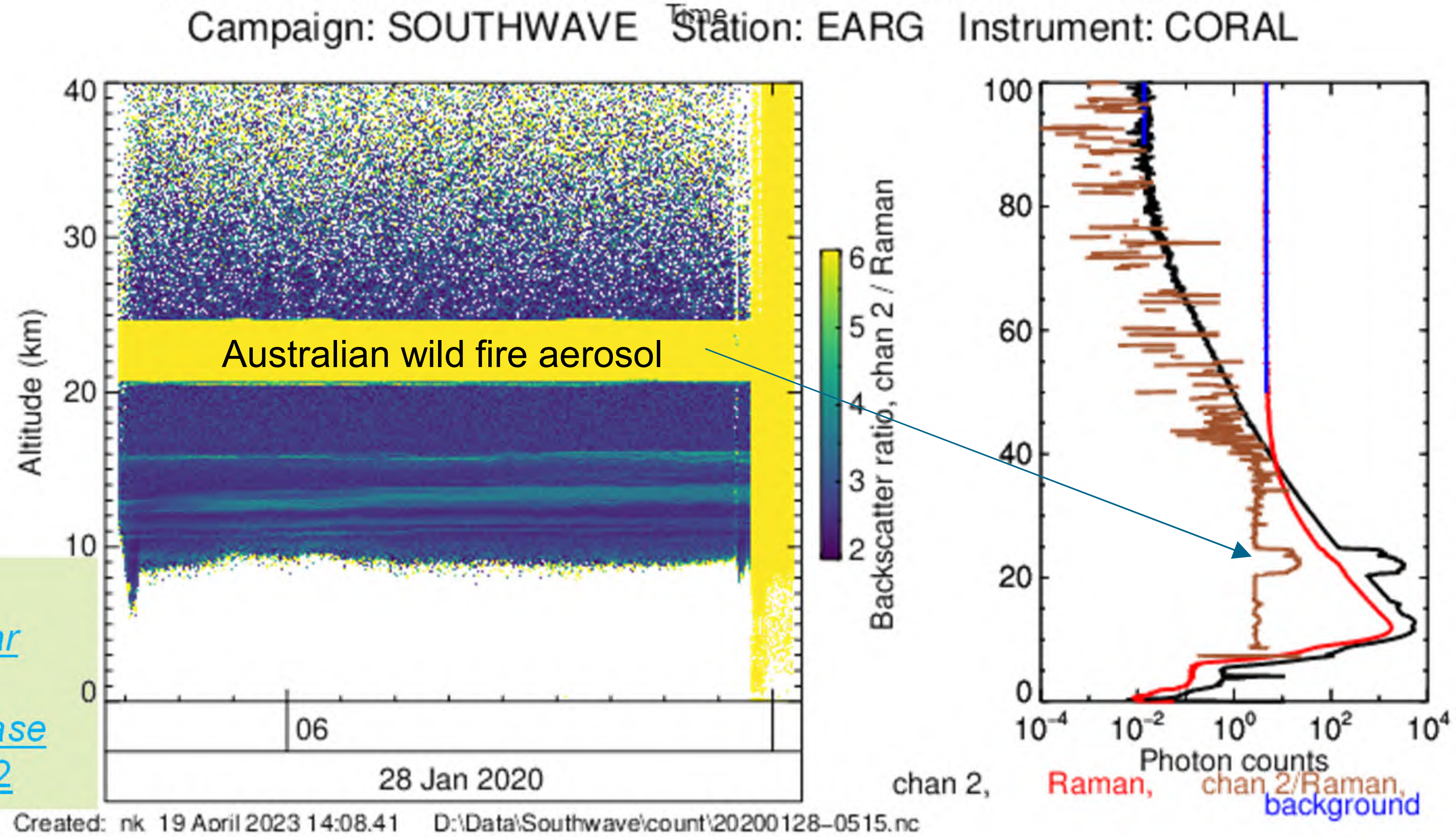
- 3 elastic channels (532 nm)
- 1 Raman channel (608 nm)

- Temperature profiles
- 15-90 km altitude
- 900 m vertical x 20 min temporal resolution
- darkness

- Nov 2017 - ongoing

- Measurement calender with quickplots at: http://extern05.pa.op.dlr.de/coral/php_calendar/calendar.php





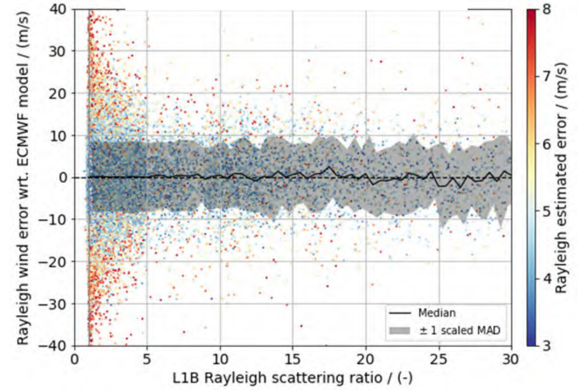
References and data availabilty:

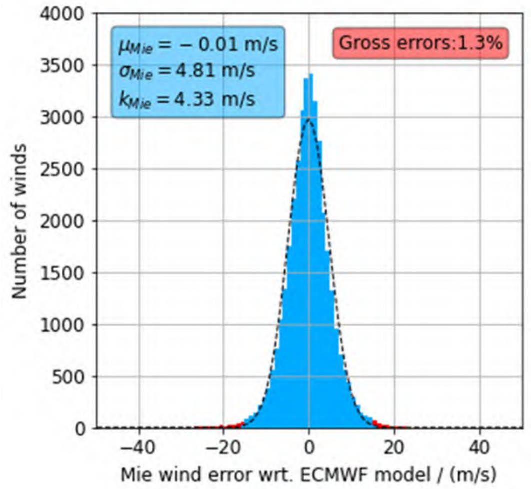
- **Kaifler, Bernd und Kaifler, Natalie** (2021) *A Compact Rayleigh Autonomous Lidar (CORAL) for the middle atmosphere.* AMT, doi: 10.5194/amt-14-1715-2021
- Ohneiser et al. (2022) *Australian wildfire smoke in the stratosphere: the decay phase in 2020/2021 and impact on ozone depletion.* ACP, doi: 10.5194/acp-22-7417-2022

Summary and Outlook

- ✓ **Four airborne campaigns were performed** for the Aeolus wind validation deploying the A2D and 2-µm DWL **in different conditions** concerning Aeolus performance, geographical region and atmospheric dynamics.
- ✓ The errors of Rayleigh and Mie winds with respect to the 2-µm reference DWL were verified to be close to the mission requirement for **bias (<0.7 m/s)** , while the **random errors were 4 – 6 m/s** (1 km range bin equivalent) for **Rayleigh clear** (degrading with decreasing atmospheric backscatter signal between Oct. 2019 and Sept. 2021) and **2 – 3 m/s for Mie cloudy.**
- ✓ The Aeolus **Rayleigh-clear wind bias does not show a dependence on the 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.
- ✓ A **combined QC approach** was developed for the Aeolus wind statistical analysis based on the **estimated error threshold and the modified Z-score**, to correct for skewed distributions of wind errors.
- ✓ Ongoing **development of L2B processor updates** is stimulated by the lower number of valid Aeolus Mie-cloudy winds compared to A2D ➔ QC based on Mie Core fit residual error **proved to 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 year.
- ➢ DLR airborne campaigns datasets remain to be relevant for **inter campaign comparison** (dependency on different conditions) and to **support and validate future processor developments for wind and potentially aerosol products for Aeolus and future space lidar missions.**

Courtesy Gilles





THANK YOU FOR YOUR ATTENTION!