Validation Campaigns for Aeolus with the ALADIN Airborne Demonstrator and 2-µm Doppler Wind Lidar Team

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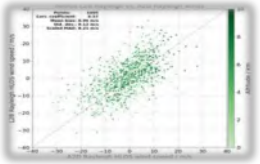
DLR aeolus DISC esa

Outline

- DLR Airborne Doppler Wind Lidars for the Validation of Aeolus

- Airborne Campaigns Overview

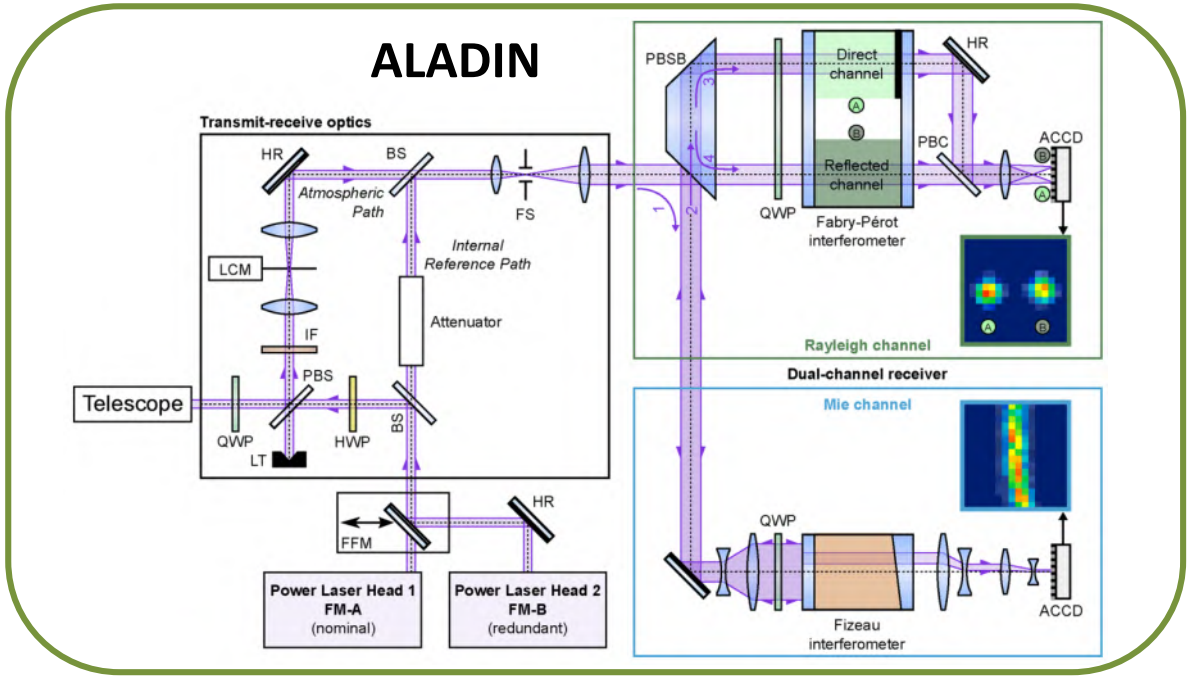


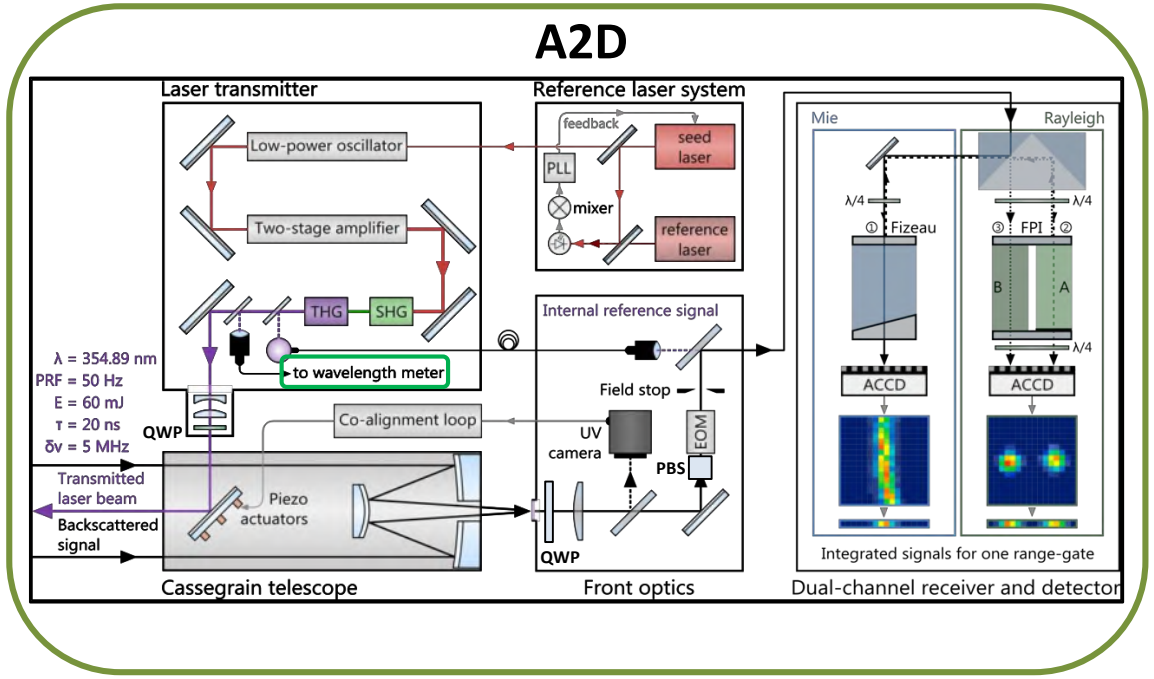
- Preliminary Analysis Topics and Results

Courtesy Gilles

- Summary

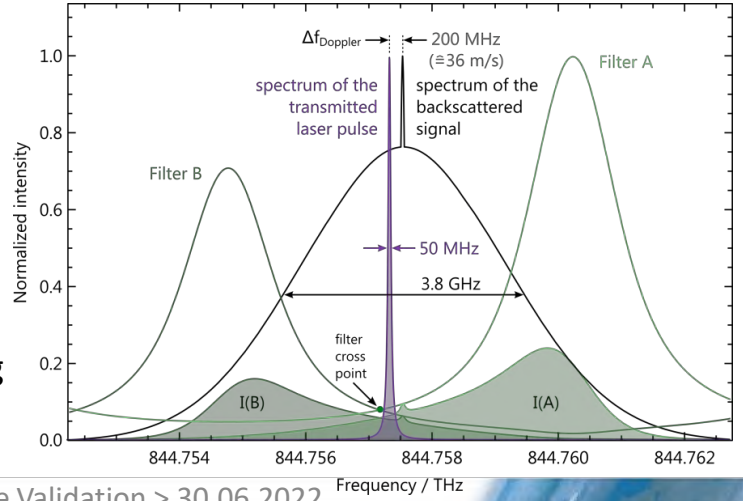
Complex New Technologies on Aeolus ➔ Verification With the Airborne Demonstrator





Doppler shift in beam direction, line-of-sight (LOS): $\Delta f = f_o \cdot 2\, v_{LOS}/c$

Measurement principal (example backscatter spectrum with scattering ratio ~1.01)



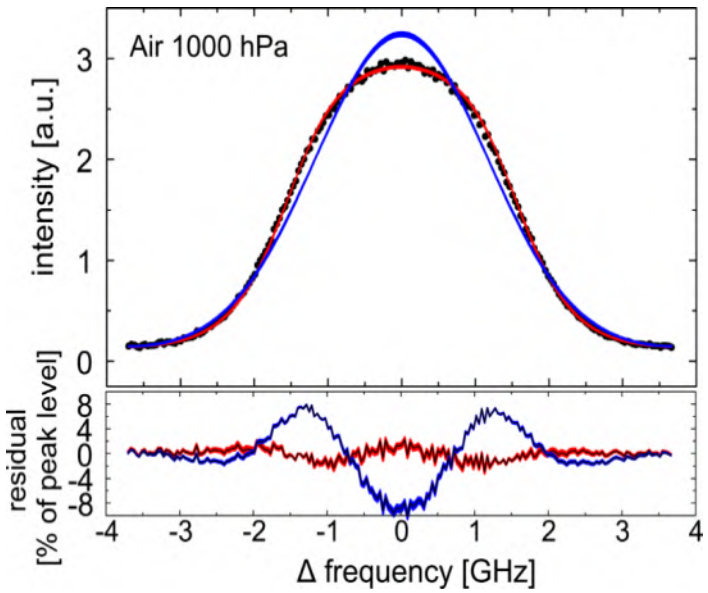
Parameter	ALADIN (Atmospheric Laser Doppler Instrument) on Aeolus	ALADIN Airborne Demonstrator (A2D)
Laser wavelength	354.8 nm	354.89 nm
Repetition rate	50.5 Hz	50 Hz
Pulse energy	53…90 mJ	60 mJ
Linewidth	30 MHz (FWHM)	50 MHz (FWHM)
Telescope diameter	1.5 m	0.2 m
LOS slant angle	35°	20°
Optical layout	Transceiver	Mono-static with active co-alignment
Receiver	Sequential Fabry-Pérot interferometers for molecular backscatter (Rayleigh channel) and Fizeau interferometer for particulate backscatter (Mie channel)	
Horizontal resolution	86.4 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

Dedicated Pre-launch Activities: Example Spectral Characterization With A2D and Related Results

First Rayleigh-Brillouin (RB) line shape measurements with atmospheric molecular returns with the A2D on the alpine research station Schneefernerhaus on Mt. Zugspitze in 2009 with horizontally pointing lidar beam

Detailed characterization of A2D Rayleigh and Mie spectrometers

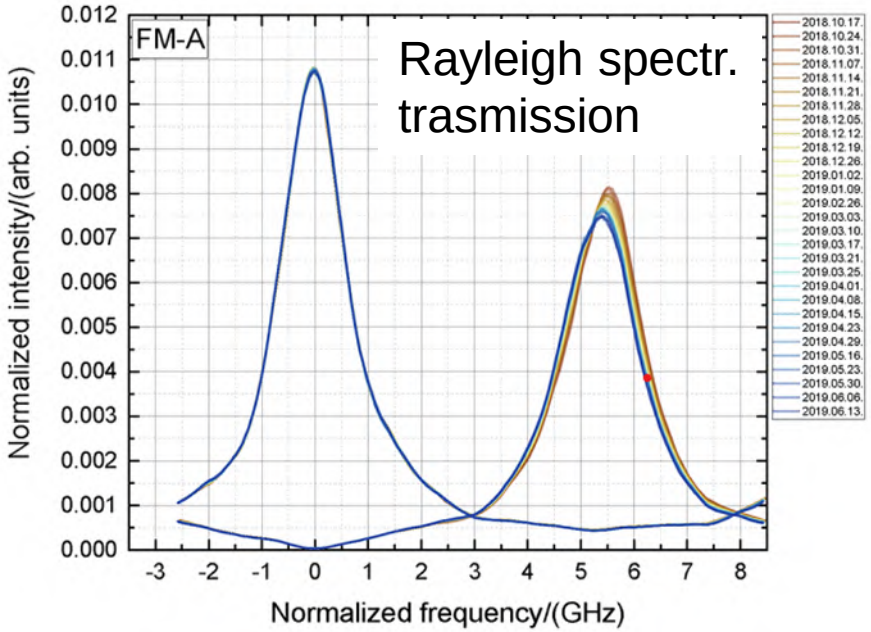
- Resolution of the RB spectrum
- Consideration in Aeolus processor confirmed



Witschas et al. (2010, 2011, 2012), Appl. Opt.

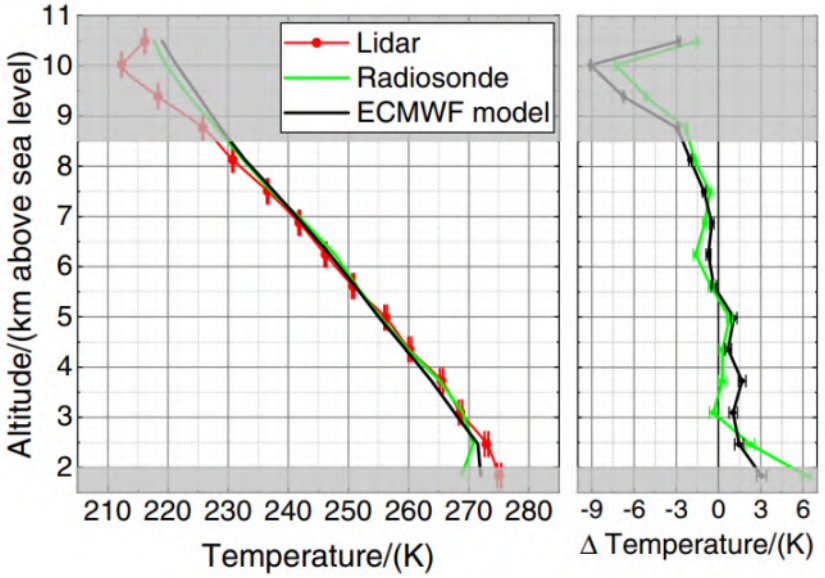
Detailed characterization of the Aeolus spectrometers

- Accurate spectral referencing between laser and receiver
- Monitoring of spectrometer performance in space relevant for wind and aerosol products calibration



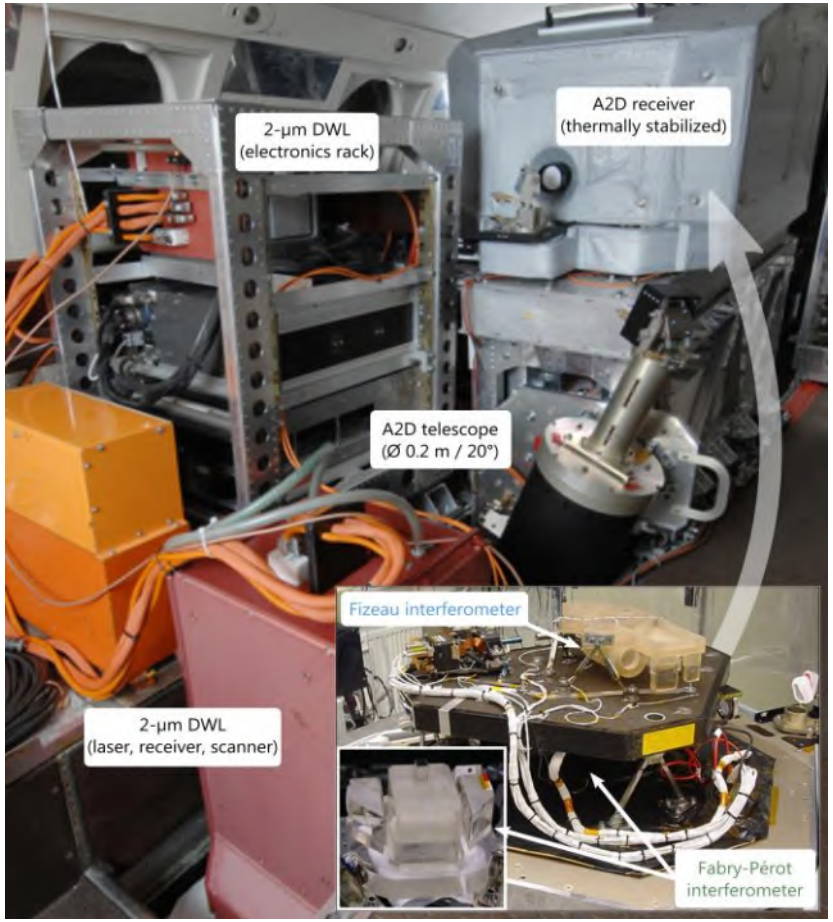
Witschas et al. (2022), AMT

A2D: First measurements of tropospheric temperature profiles from ground and airborne during daylight with a high spectral resolution lidar



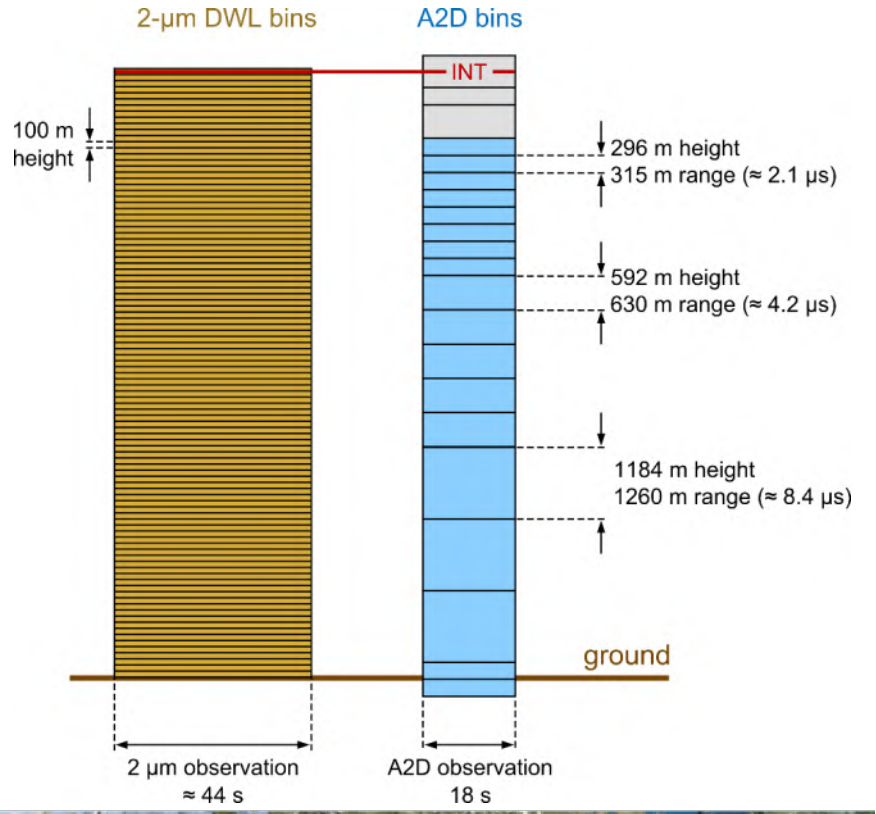
Airborne temperature profile, Iceland 2016
Witschas et al. (2014 & 2021), Optics Letters

Aeolus Wind Validation at DLR with the A2D and the 2-µm Doppler Wind Lidars



- The A2D was operated for measurements from ground and on the DLR Falcon 20 aircraft mostly with the scanning coherent 2-µm Doppler wind lidar (DWL) providing reference profiles of windspeed and –direction
- Continuous improvement of the A2D and refinement of operational and analysis methods as a result of **several ground and airborne campaigns during the mission implementation phase were fundamental to the early Aeolus success (wind already 3 weeks after launch)**

Parameter	A2D	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}



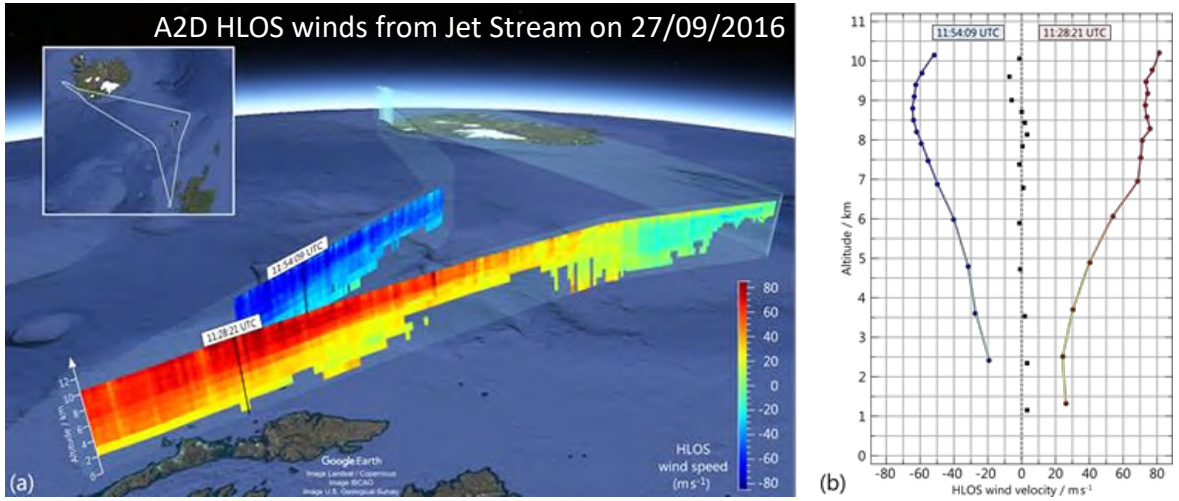
Lux et al. (2022), **AMT**

Witschas et al. (2020), **AMT**

Major Airborne Campaigns Before Launch (DLR/NASA/CNES)

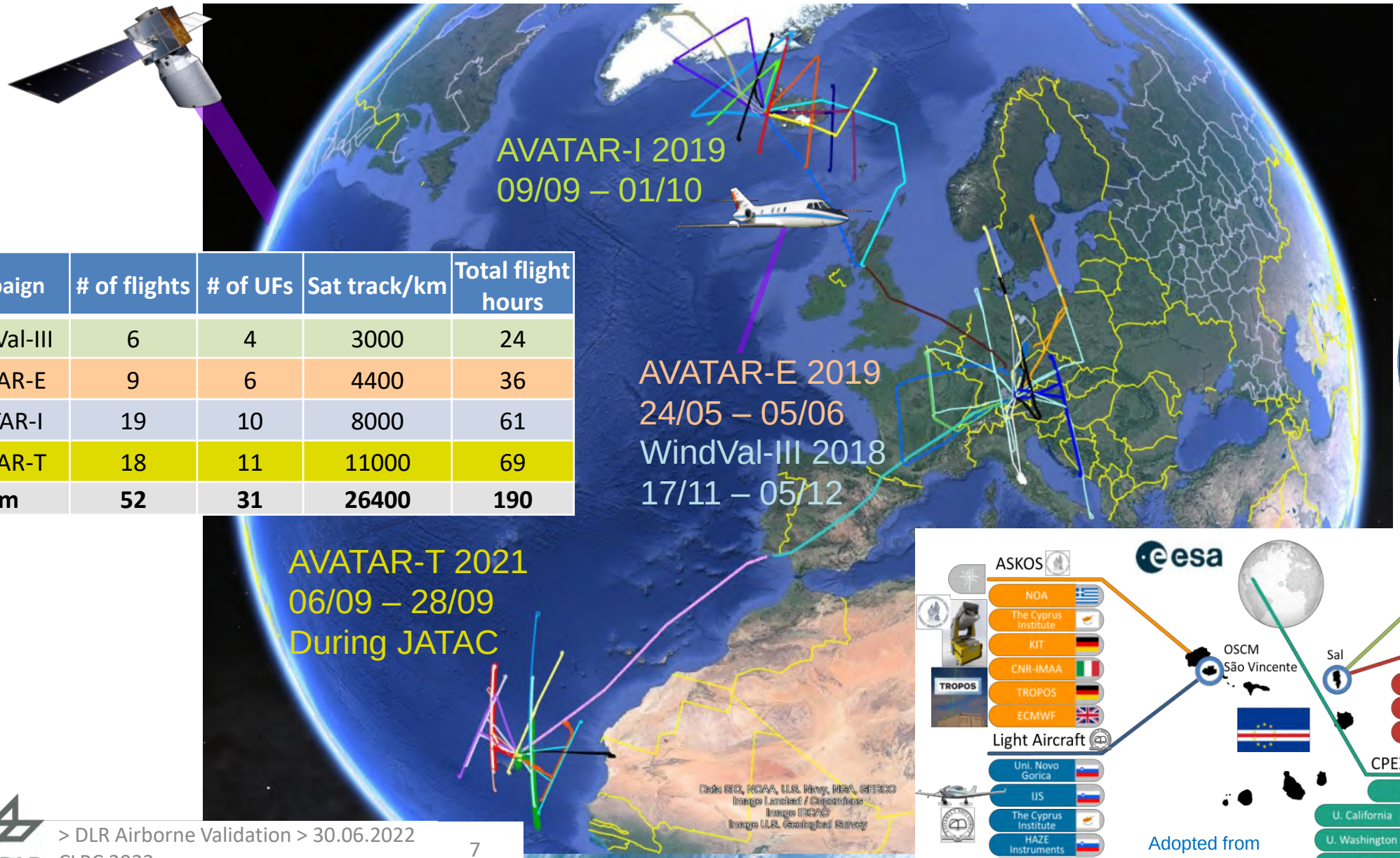
- The A2D together with the 2-µm DWL tested mission procedures and algorithms for the complex new technology on Aeolus in flight
  2015 & 2016 in Iceland
- Complements instrument tests by ESA and space industry with atmospheric measurements

- **Demonstrated: Aeolus measurement principle works reliably also in harsh airborne environmental conditions**
- **More than 150 recommendations for the Aeolus mission derived from A2D activities for instrument alignment, operation, retrieval algorithms and calibration/validation already before launch**



Reitebuch et al. (2009), **JAOT**; Reitebuch (2012); **Springer**; Lemmerz et al. (2017), **AO**; Lux et al. (2018), **AMT;** Marksteiner et al. (2018), **Remote Sensing;** Witschas et al (2017), **JAOT**

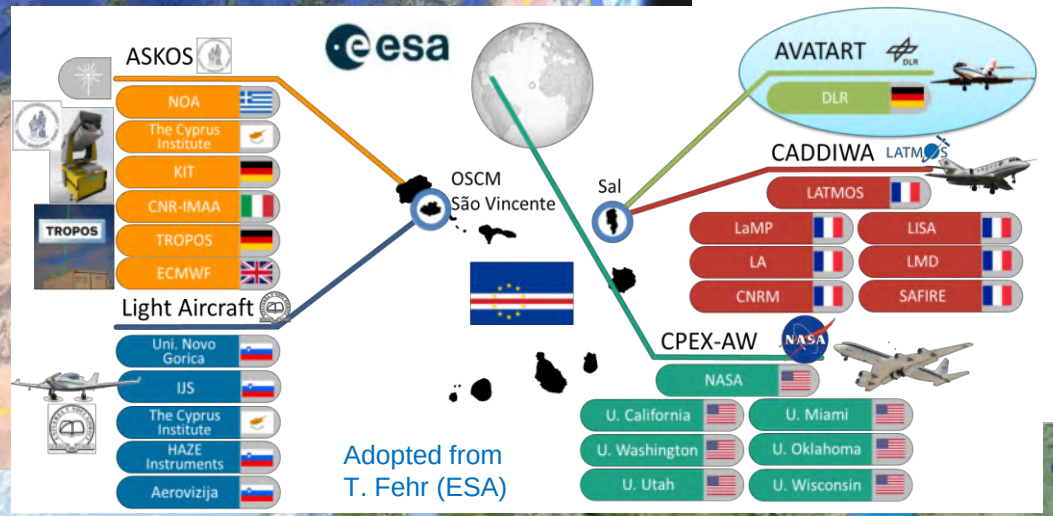
DLR Aeolus Airborne Campaigns Locations Overview



Campaign	# of flights	# of UFs	Sat track/km	Total flight hours
WindVal-III	6	4	3000	24
AVATAR-E	9	6	4400	36
AVATAR-I	19	10	8000	61
AVATAR-T	18	11	11000	69
Sum	**52**	**31**	**26400**	**190**

Aeolus Validation Through Airborne Lidars in Iceland

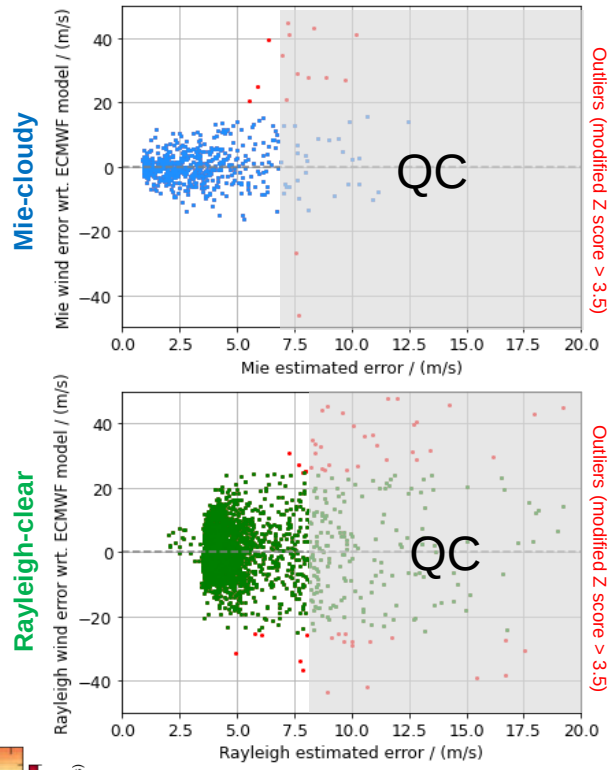
Aeolus Validation Through Airborne Lidars in the Tropics
Cabo Verde - September 2021



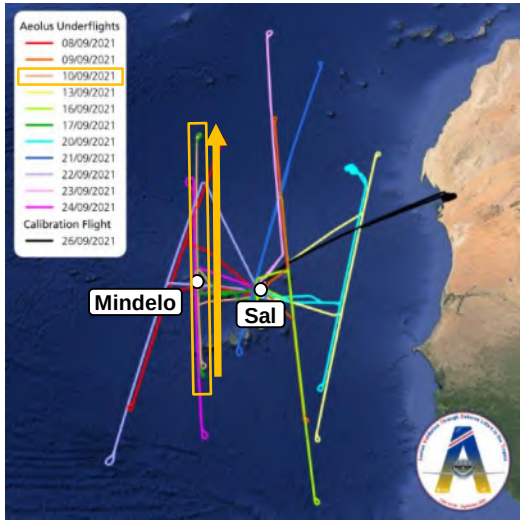
Adopted from
T. Fehr (ESA)

Current Topics of the AVATAR-T Data Analysis

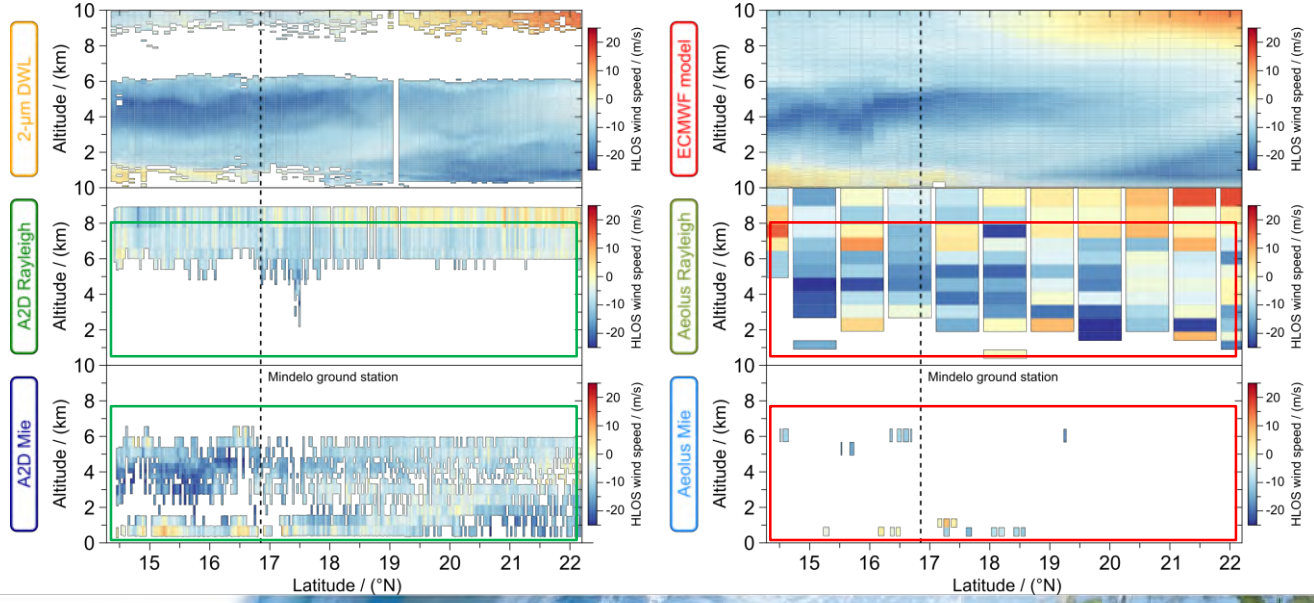
- Aeolus Mie cloudy gap w.r.t. A2D (and 2-µm DWL) coverage within the dust laden altitudes up to 7 km
- Study Mie signal influence on Rayleigh wind error and bias in this area and potential for a Mie – dust wind product (in addition to Mie-coudy), improved QC…
- Aeolus L2B winds quality control: Develop strategy to balance outliers and the Estimated Error (EE) influence on statistical results of instrumental bias and random errors for each channel ➔ **combination of EE-threshold and modified Z-score (Z_m)**



Falcon flight tracks from the 11 Aeolus underflights and the A2D calibration flight



Wind data from the 2-µm DWL, the ECMWF model as well as the Aeolus and A2D Rayleigh and Mie channels from the Aeolus underflight on 10 September 2021

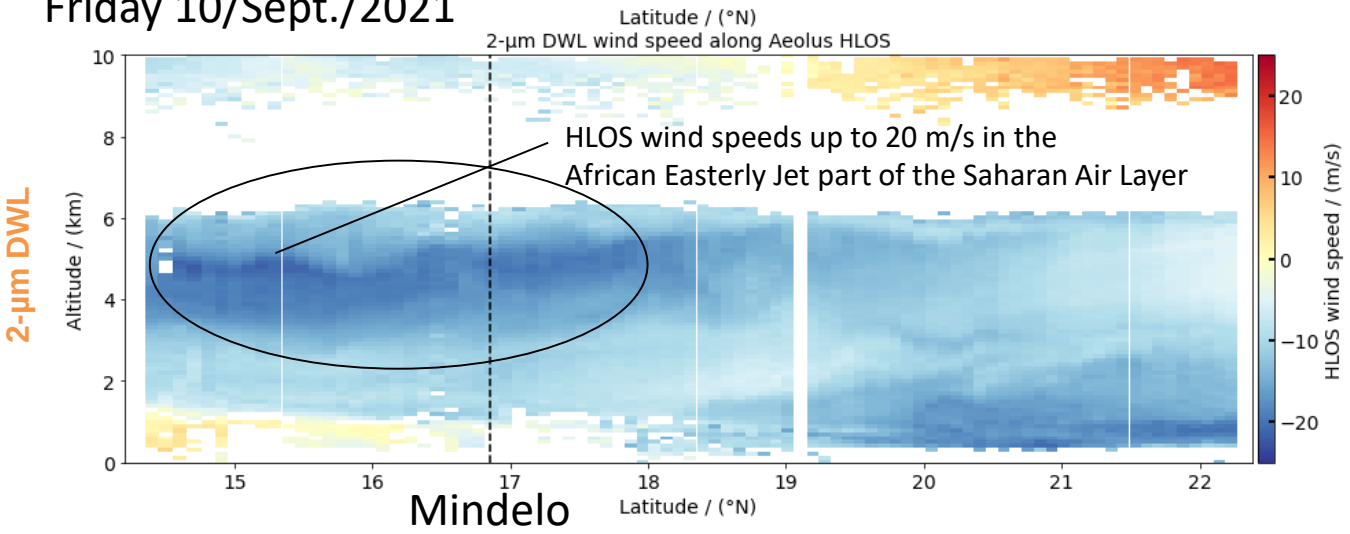


$$Z_{m,i} = \frac{x_i - x_{median}}{\text{scaled MAD}} \text{ with}$$

$$\text{scaled MAD} = 1.4826 * \text{median}(|x_i - x_{median}|)$$

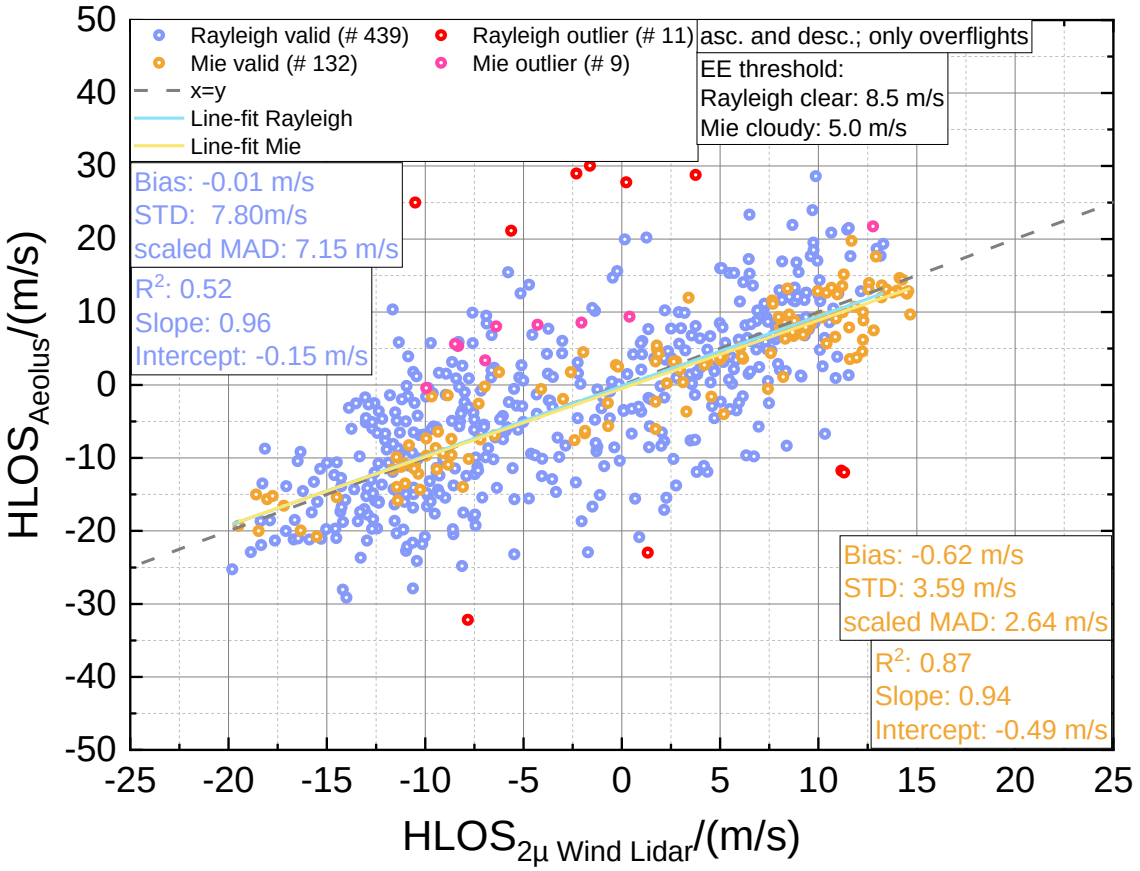
Statistical Comparison of L2B and 2-µm DWL winds - AVATART

Friday 10/Sept./2021



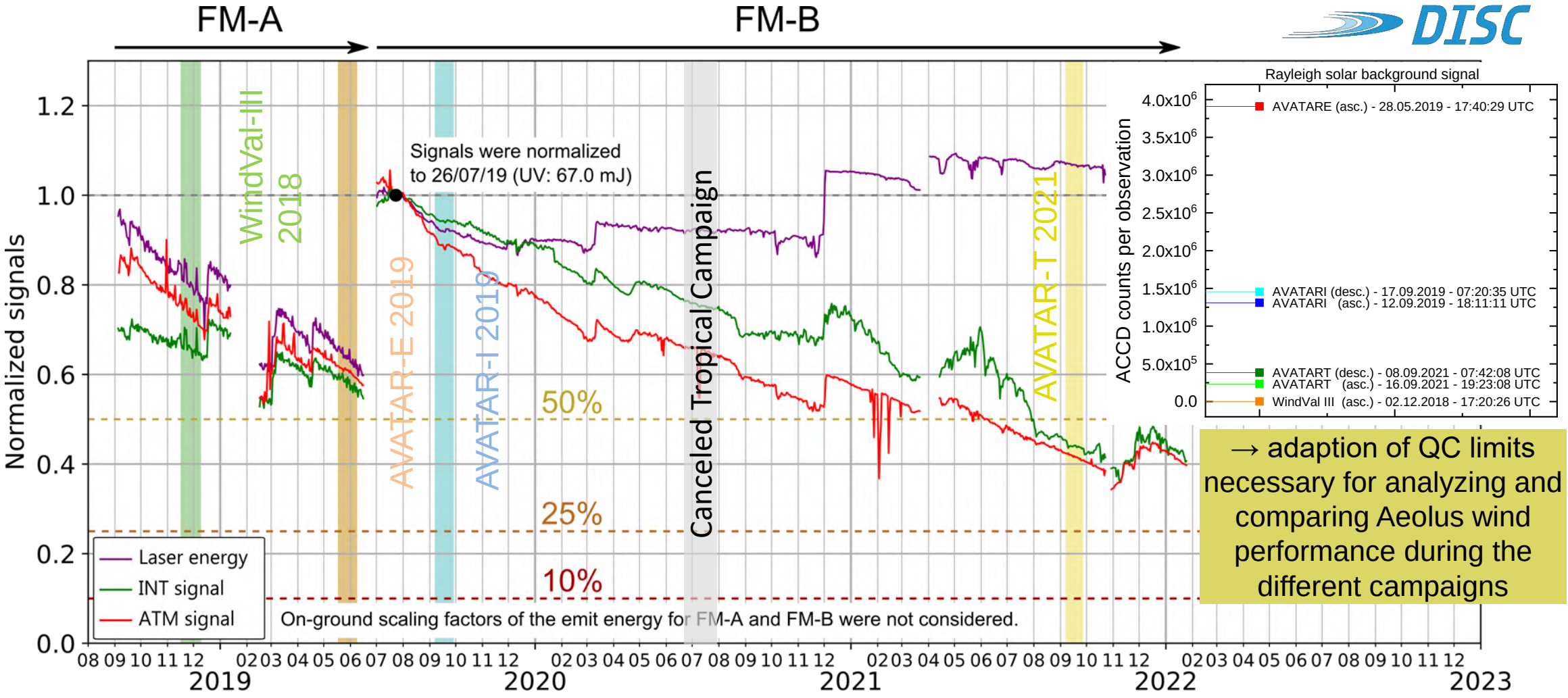
- → **Systematic error is within the specifications (0.7 m/s)** for both Ray.-clear/Mie-cloudy winds
- → Largest **random error of 7.2 m/s** for the Ray.-clear winds due to the low signal levels (and range gate size)
- → The **random error** of Mie winds **(2.6 m/s)** is less affected, as the Mie winds are mostly from cloud returns and the SNR is mainly defined by the scattering ratio (particle load) and less by the transmitted laser energy

Statistical comparison of L2B and 2-µm DWL winds for all AVATART data



Credits to Benjamin Witschas and Stephan Rahm

Airborne Campaigns Timeline and Aeolus Performance History



→ adaption of QC limits necessary for analyzing and comparing Aeolus wind performance during the different campaigns

Aeolus RBS: Initial (w/o DEM) VAMP AVATARI-2 Saturn-2

Baselines: 19/11/18 L1Bp v7.04, B-02; 16/5/19 B-03; 5/9/19 B-06 (+ 1st and 2nd re-processed B-10 and B-11) B12

Adapted plot from Oliver Lux

Rayleigh solar background observations provided by K. Schmidt, DLR, DISC

Summary and Conclusion

Aeolus – 2-µm DWL statistical comparison results history for the Aeolus processor versions active during the time of the campaign

*** For better comparison between campaigns, Rayleigh random errors are calculated for 1 km range gates 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)**

**** ATM signal is given in arb. units and calculation as a mean per orbit, not for the particular campaign's region**

Campaign/data set	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	2.1	2.3	4.0/3.9	2.2/2.0	53	0.75
AVATARE	-4.6	-0.2	4.4/4.3	2.2/2.0	42	0.6
AVATARI (ascending)	0.0	-0.2	4.3/4.2	2.8/2.7	62	0.9
AVATARI (descending)	1.8	-0.6	3.9/3.8	2.5/2.3	62	0.9
AVATART (preliminary)	-0.0	-0.6	6.2/6.1	2.6/2.4	72	0.4

- **4 airborne campaigns** were performed for Aeolus in-orbit validation with the A2D and 2-µm DWL with a **total of 52 flights, 26400 km along the Aeolus track**
- Aeolus performance **characterization** during lifetime **under different conditions** concerning Aeolus signal and solar back-ground, geographical regions and atmospheric dynamics
- Thanks to A2D (same technology, but higher resolution) and the 2-µm DWL as a reference, Aeolus performance specific topics are identified and studied with the goal to contribute to further processor upgrades like e.g. mitigating **Mie contamination of Rayleigh clear winds** or **realizing a Mie – Aerosol product**
- **Aeolus QC-methods** are developed which are applicable to all campaigns and the validation community
- The airborne campaign datasets remain relevant for the **validation of future processor versions**

➔ Do a wind mission with support from an airborne demonstrator