Aeolus Airborne Wind Validation Campaigns at DLR

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Outline

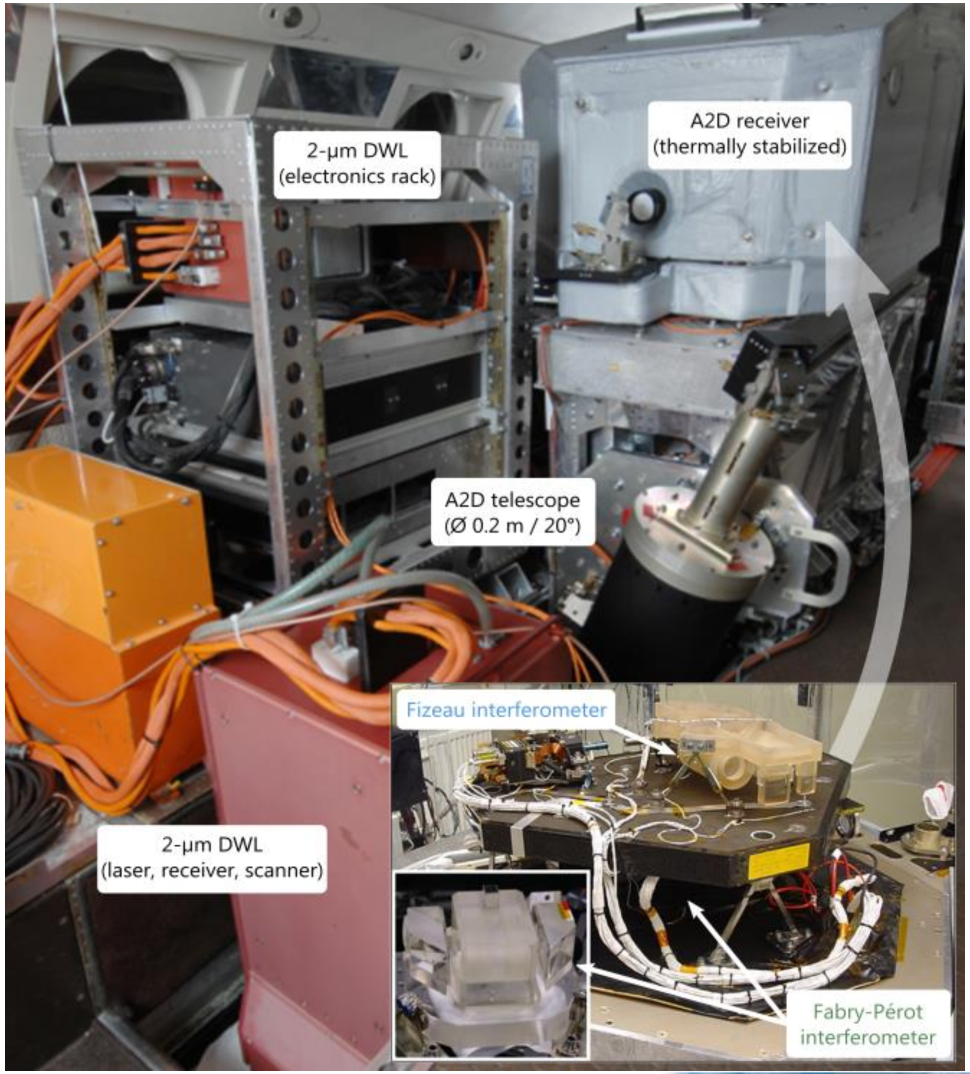
- Aeolus airborne validation Doppler wind lidar systems @ DLR
- Overview of validation campaigns in 2018 and 2019
- Selected A2D results
- 2-µm reference system wind comparison results
- Outlook

Aeolus Validation Through Airborne Lidars in Europe

Aeolus Validation Through Airborne Lidars in Iceland

Doppler Wind Lidar Instrumentation of the DLR-Falcon Aircraft

- **ALADIN Airborne Demonstrator (A2D)** direct-detection wind lidar **and coherent 2-µm wind lidar** on-board the same aircraft (DLR Falcon)



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)	10 or 20 shots = 200 or 400 ms	single shot = 2 ms
Temporal averaging product (horizontal)	14 s (+4 s data gap)	1 s per LOS (500 shots), 38 s scan (LOS)
Horizontal resolution @ 200 m·s^{-1} = 720 km/h = 12 km/min.	3.6 km (18 s)	0.2 km LOS, 7.6 km scan
Precision (random error)	1.5 m/s (Mie) 1.8 m/s (Rayleigh)	< 1 m/s
Accuracy (systematic error)	0.2 m/s – 1 m/s	< 0.1 m/s

Marksteiner et al. (2018), **Remote Sensing**

Witschas et al. (2017), **J-Tech**

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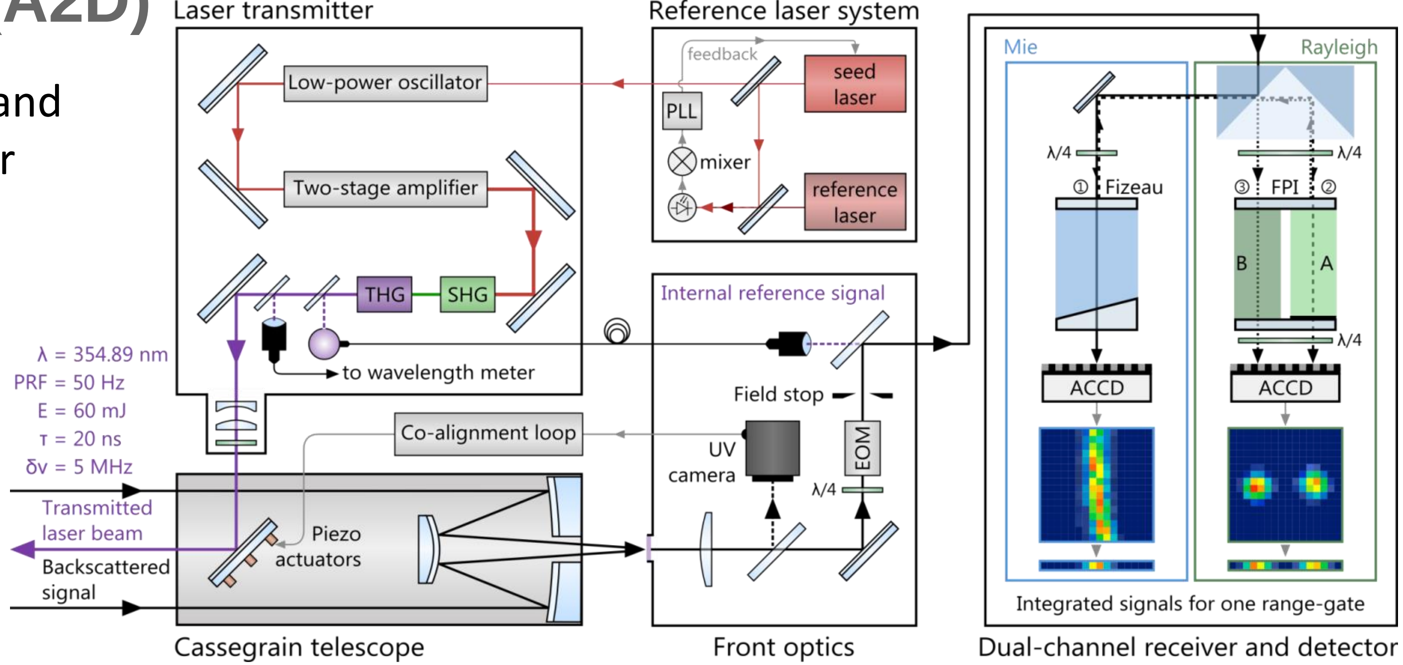
Lux et al. (2018), **AMT**

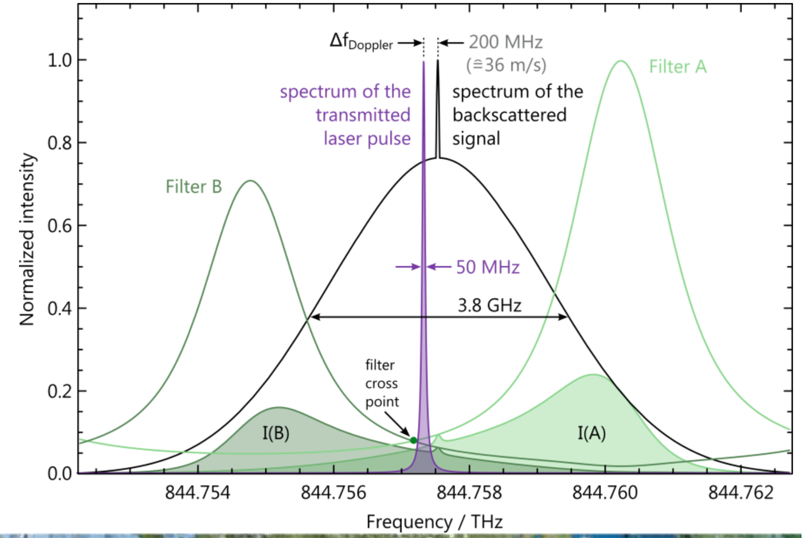
The ALADIN Airborne Demonstrator (A2D)

A2D is build around the Aeolus pre-development Fizeau and Fabry-Perot interferometers for particulate and molecular backscatter wind signals
➔ **Aeolus' airborne twin**

Continuous development of the A2D together with a refinement of operational and analysis methods has been relevant for the Aeolus satellite mission, since 2005 (various ground, 4 pre- and 3 post-launch airborne camp.)
➔ **Integral part of the quick mission success after launch**



- Demonstrate Aeolus lidar technology capabilities
  ➔ LOS wind systematic errors < 0.2 m/s and random errors < 1.8 m/s demonstrated for both channels w.r.t. 2-µm reference lidar during the recent campaigns
- Ongoing investigations (e.g. Mie channel non-linearity, hot pixel investigation, radiometric performance, QC and channel cross-talk…)



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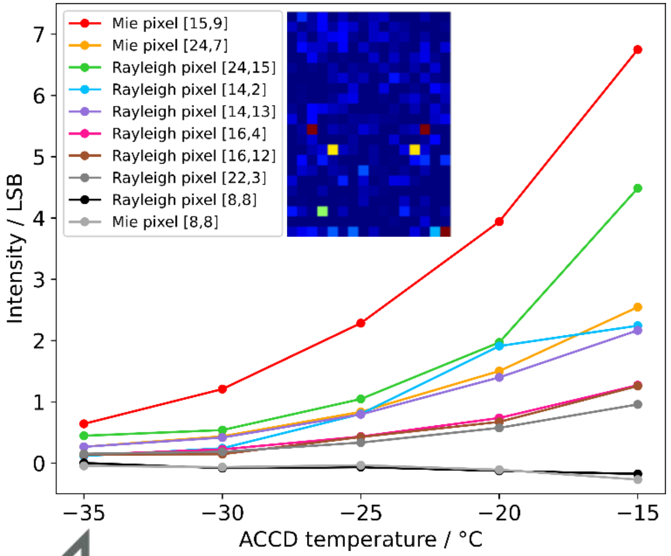
The A2D as a testbed for instrument studies and processor refinements

Hot pixel investigation

- Dark currents of A2D ACCDs were measured at different temperatures and accumulation settings
- The signal offsets were found to increase nonlinearly with temperature; only 1 hot pixel (>1 LSB) at T = -30°C

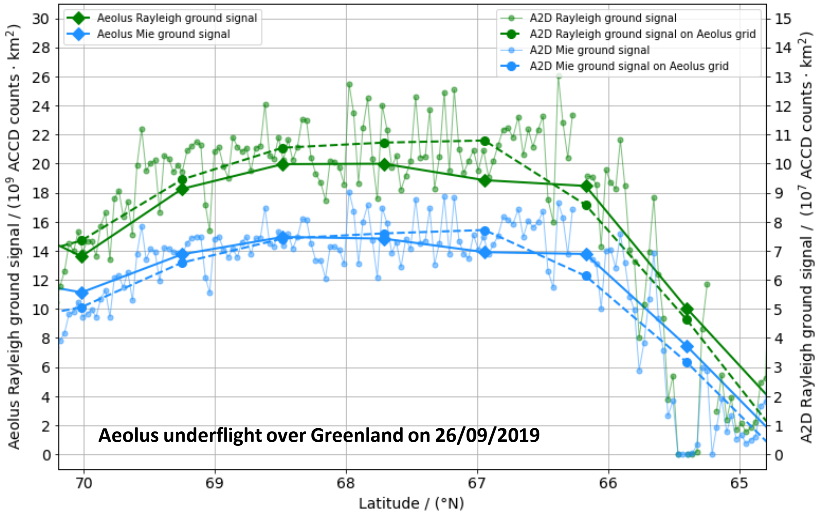
→ **Studies supported the root cause analysis and helped to explore possible mitigation strategies**



Radiometric performance comparison

- Atmospheric and ground return signals were measured during an underflight over Greenland at cloud-free conditions
- ALADIN Rayleigh ground signals over snow/ice are only 35 times higher than Rayleigh clear atmospheric return signals, whereas the factor is 60 for the A2D

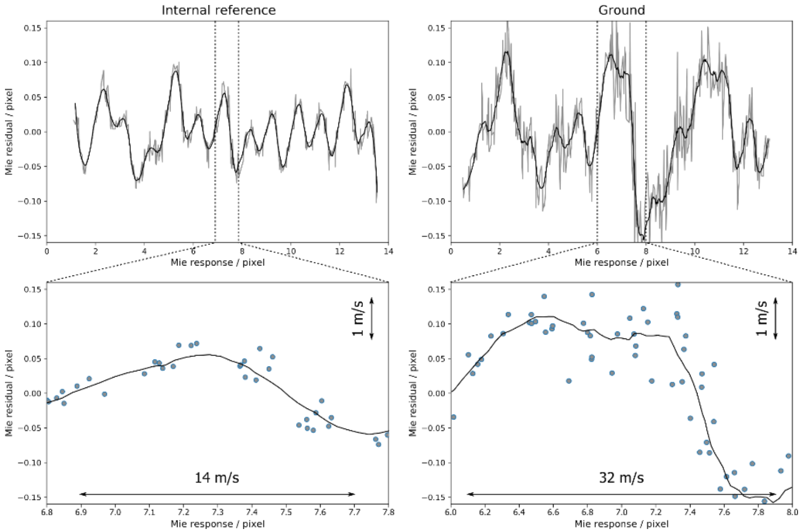
→ **Comparison of Rayleigh GR-to-ATM signal ratios confirmed the results from E2S simulations**



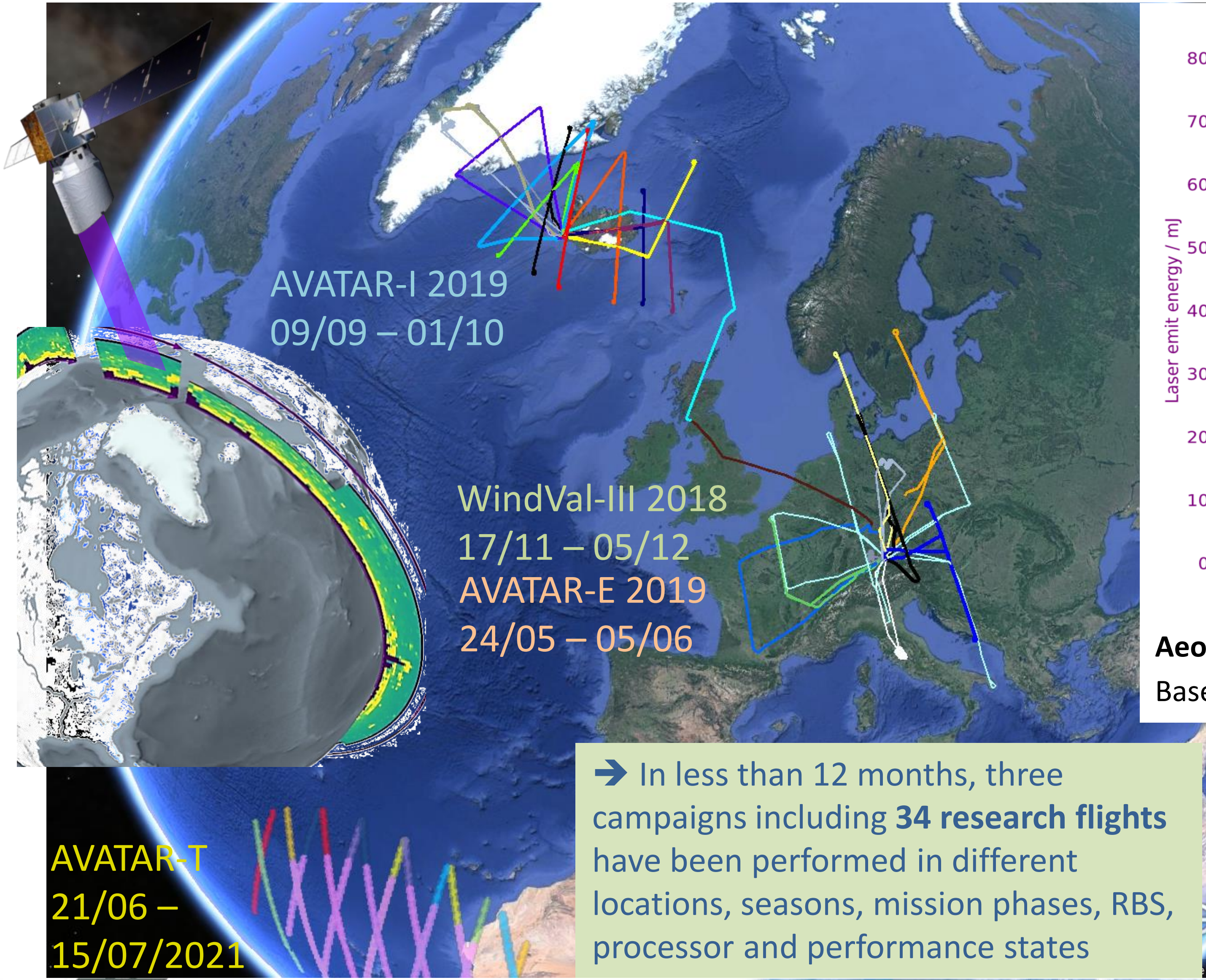
Mie nonlinearity correction

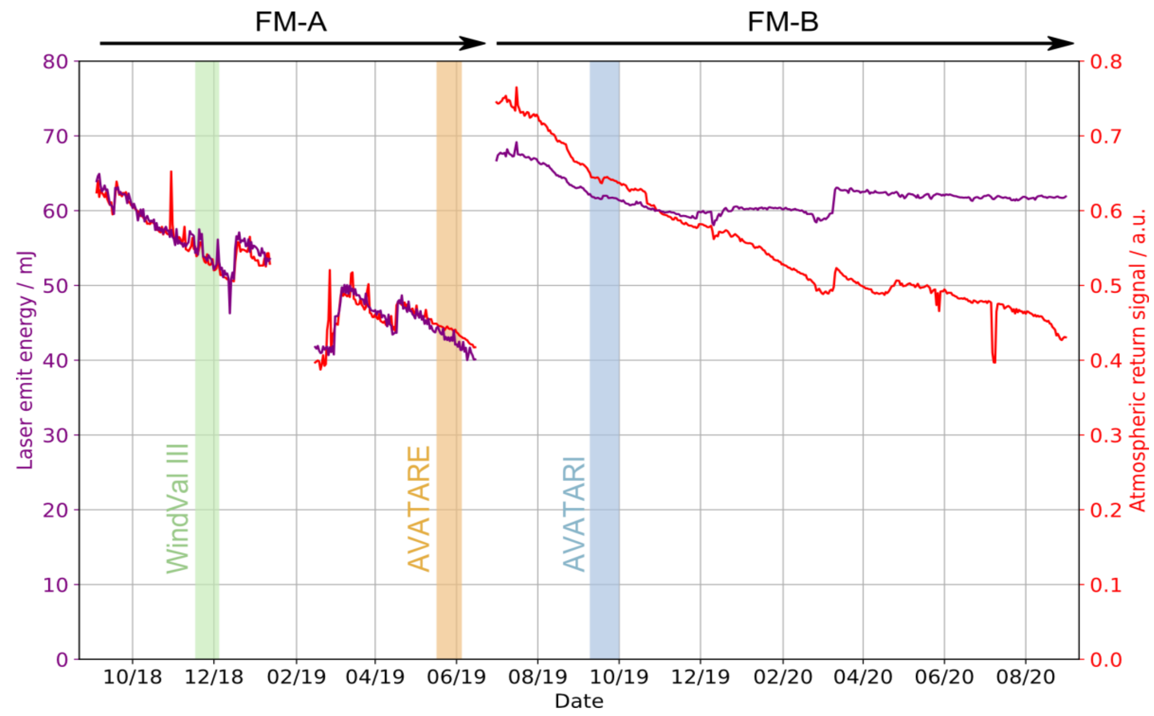
- MRCs from the airborne campaigns were analyzed to determine a relationship between Mie response and the fit residual
- Implementation of the Mie nonlinearity correction scheme improved the accuracy of the Mie winds and ground velocities

→ **A2D processor modifications and their evaluation provides approaches for refinements of the Aeolus processors**



Aeolus Post- Launch Airborne Validation Campaigns 2018 and 2019





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

Baselines: 19/11/18 L1Bp v7.04, B-02; 16/5/19 B-03; 5/9/19 B-06

➔ In less than 12 months, three campaigns including **34 research flights** have been performed in different locations, seasons, mission phases, RBS, processor and performance states

Campaign	# of Flights	# of UFs	Sat Track/km	Total Flight hours
WindVal-III	6	4	3000	24
AVATARE	9	6	4400	36
AVATARI	19	10	8000	61
Sum	**34**	**20**	**15400**	**121**

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

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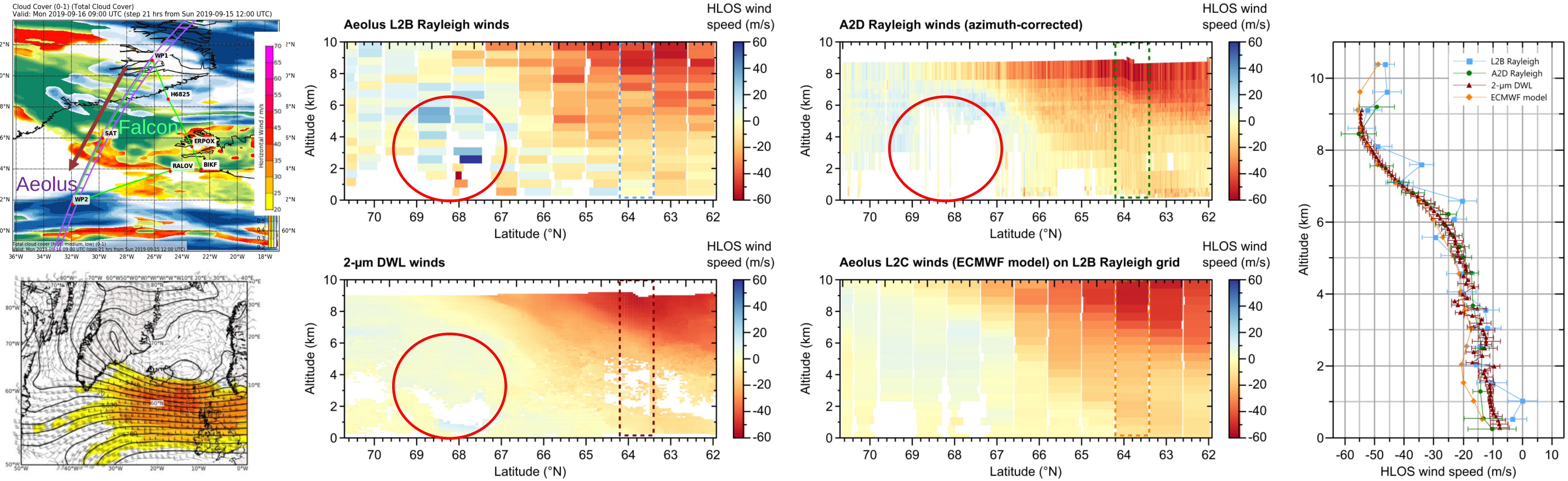
AVATAR-I example: North Atlantic Jet Stream east of Greenland on 16/09/19



- Excellent data coverage of Aeolus Rayleigh, 2-µm DWL and A2D Rayleigh winds
- Detection of strong westerly winds with horizontal wind speeds of up to 60 m/s and high vertical wind gradients >10 (m/s)/km
- Some larger Rayleigh wind errors obvious for regions of higher aerosol load (erroneous A2D Rayleigh winds are effectively filtered out by Mie SNR threshold) ➔ Further investigation with A2D vs. Aeolus cross-talk and QC ongoing

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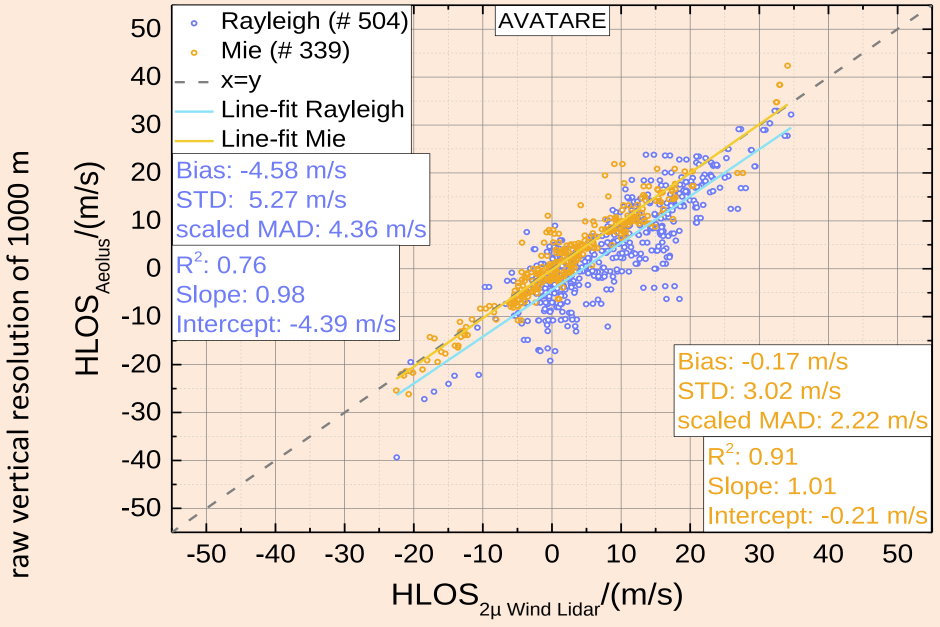
Only Aeolus data with an estimated error of < 8 m/s (Rayleigh) and < 4 m/s (Mie) are considered.

2-µm vs. Aeolus winds statistical comparison

AVATAR-E Rayleigh and Mie winds

6 ascending-orbits



AVATAR-I Rayleigh and Mie winds

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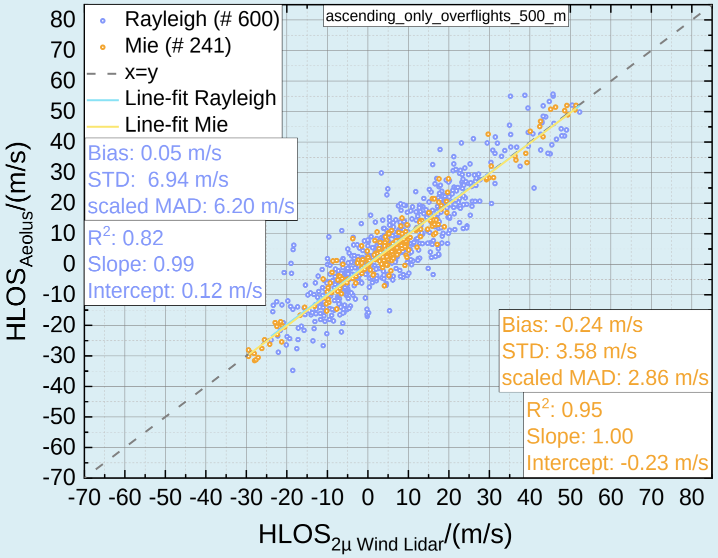
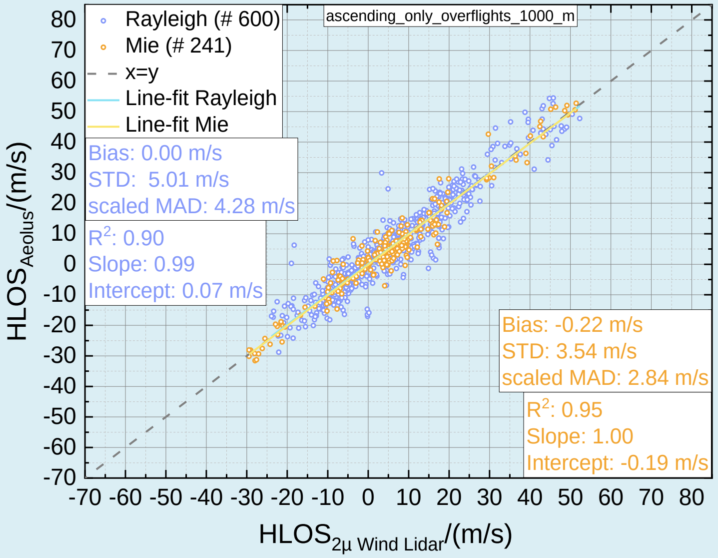


raw vertical resolution of 500 m



data averaged to 1000 m range bins for comparison with previous campaigns

A doubling of the signal level leads to a decrease of the Rayleigh-clear random error by $\sqrt{2}$

➔ the Rayleigh-clear wind random error is Poisson noise limited

➔ Rayleigh winds directly benefit from signal recovery

$$\text{scaled MAD} = 1.4826 \cdot \text{median}\left(\left|v_{\text{diff}_{\text{HLOS}}} - \text{median}\left(v_{\text{diff}_{\text{HLOS}}}\right)\right|\right)$$

The scaled MAD (Median Absolute Deviation) is less sensitive to outliers and identical to the standard deviation, if the analysed data are normally distributed

→4 descending-orbit results – see back-up slides

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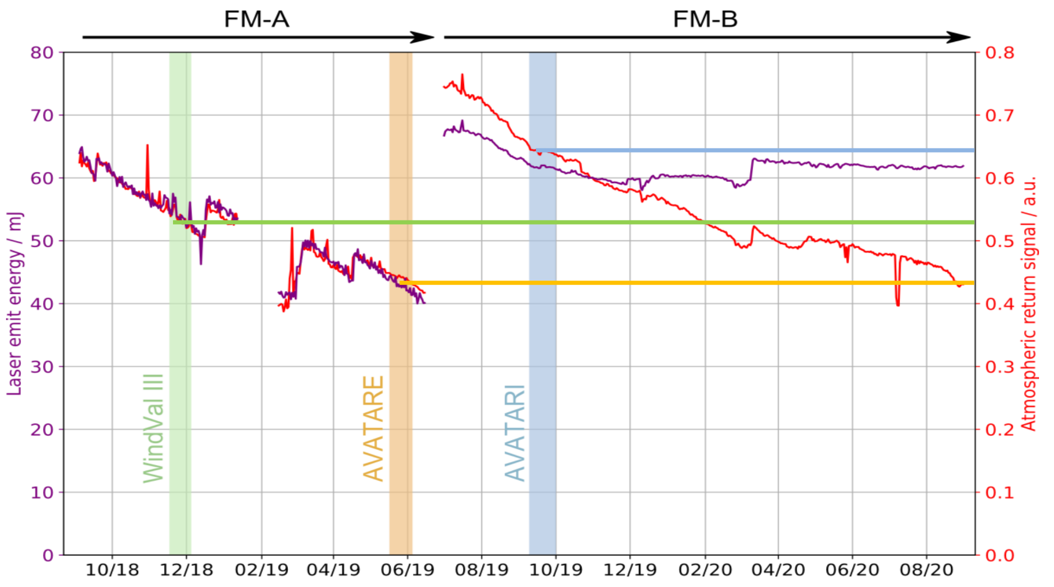
2-µm vs. Aeolus statistical comparison overview for the three campaigns

* systematic error of the 2-µm DWL is neglected, the random error is considered to be 1 m/s and is corrected

Campaign/data set	*Systematic error/(m/s)*		Random error (scaled MAD)/(m/s)		Mean Laser Energy PD 74/(mJ)
	Rayleigh	Mie	Rayleigh	Mie	
WindVal III	2.1	2.3	4.0/3.9	2.2/2.0	53
AVATARE all flight legs	-4.6	-0.2	4.4/4.3	2.2/2.0	42
AVATARI asc. 500 m	0.1	-0.2	6.1	2.7	62
AVATARI desc. 500 m	1.8	-0.5	5.9	2.2	62
AVATARI asc. 1000 m	0.0	-0.2	4.2	2.7	62
AVATARI desc. 1000 m	1.8	-0.6	3.8	2.3	62

- Scaled MAD first values denotes the one obtained from the statistical , the second value denotes the one that is corrected for the 2-µm DWL random error of 1 m/s.
- Only Aeolus data with an estimated error of smaller than 8 m/s (Rayleigh) and 4 m/s (Mie) are considered.



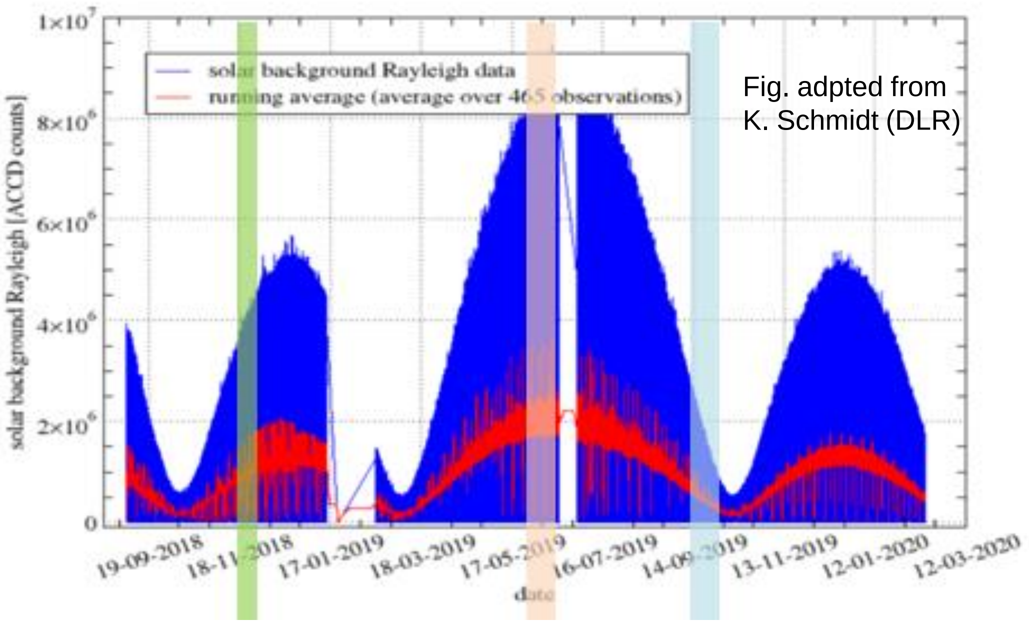


Fig. adpted from K. Schmidt (DLR)

➔ Higher Rayleigh random error expected for AVATARE due to lower atmospheric return SNR

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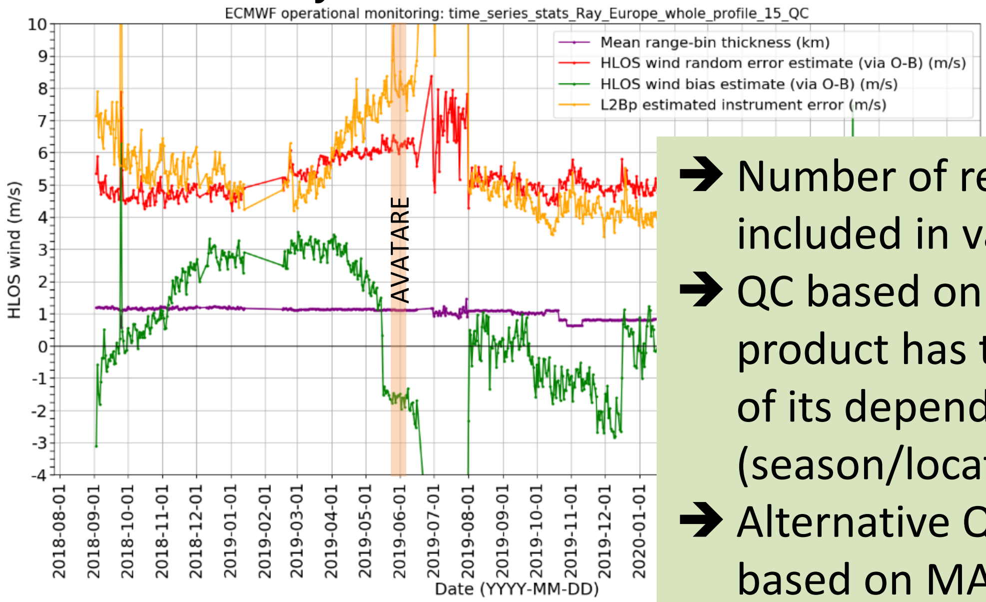
Aeolus Rayleigh random error vs. 2-µm DWL winds - comparison to the L2B reported estimated error

- Analysis by Mike Rennie, based on O-B statistics shows that the random error was remarkably overestimated by about **2 m/s** in the AVATARE frame
- By increasing the est. err. threshold to e.g. 12 m/s, the random error for AVATARE gets comparable to other data

→ a data selection based on the est. error (8 m/s threshold) excludes too many data points which in turn reduces the derived random error

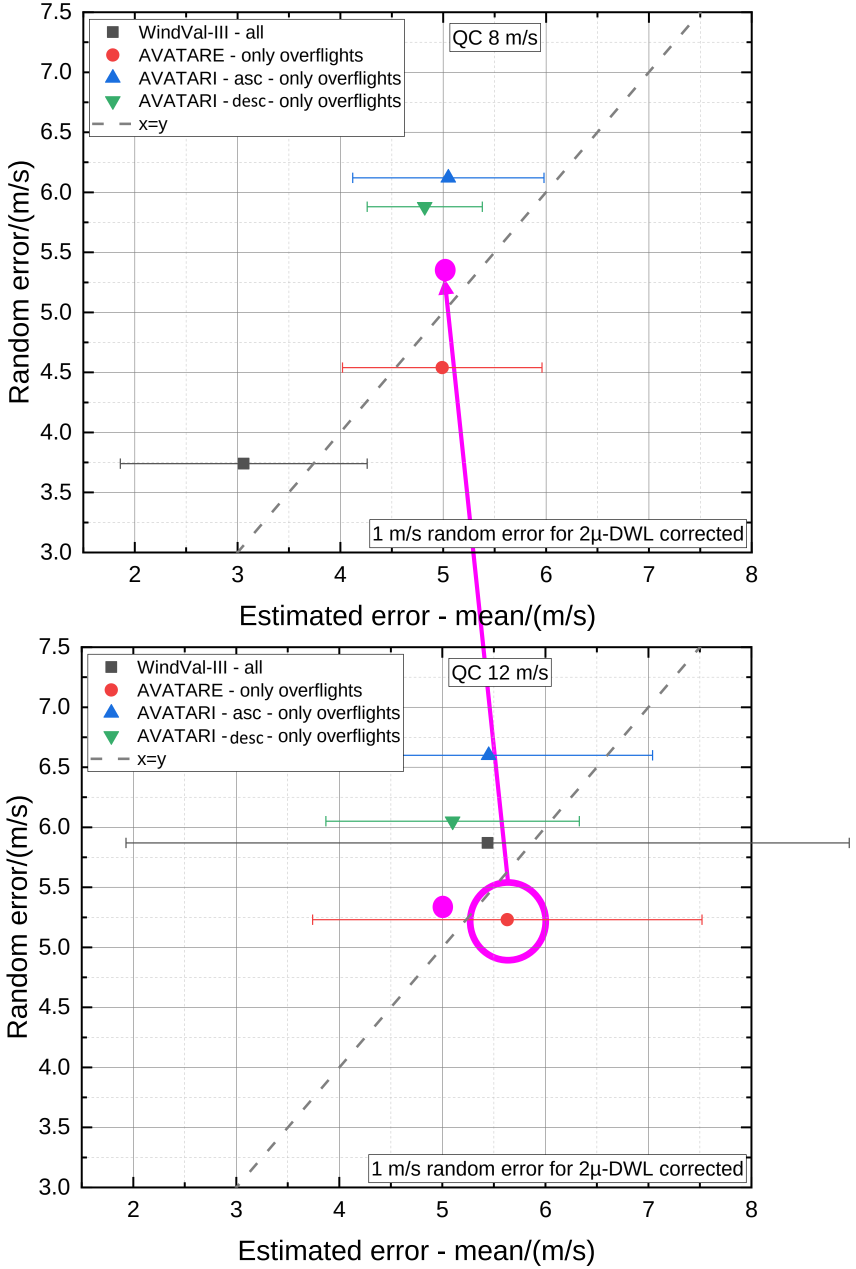
Courtesy Mike Rennie, ECMWF



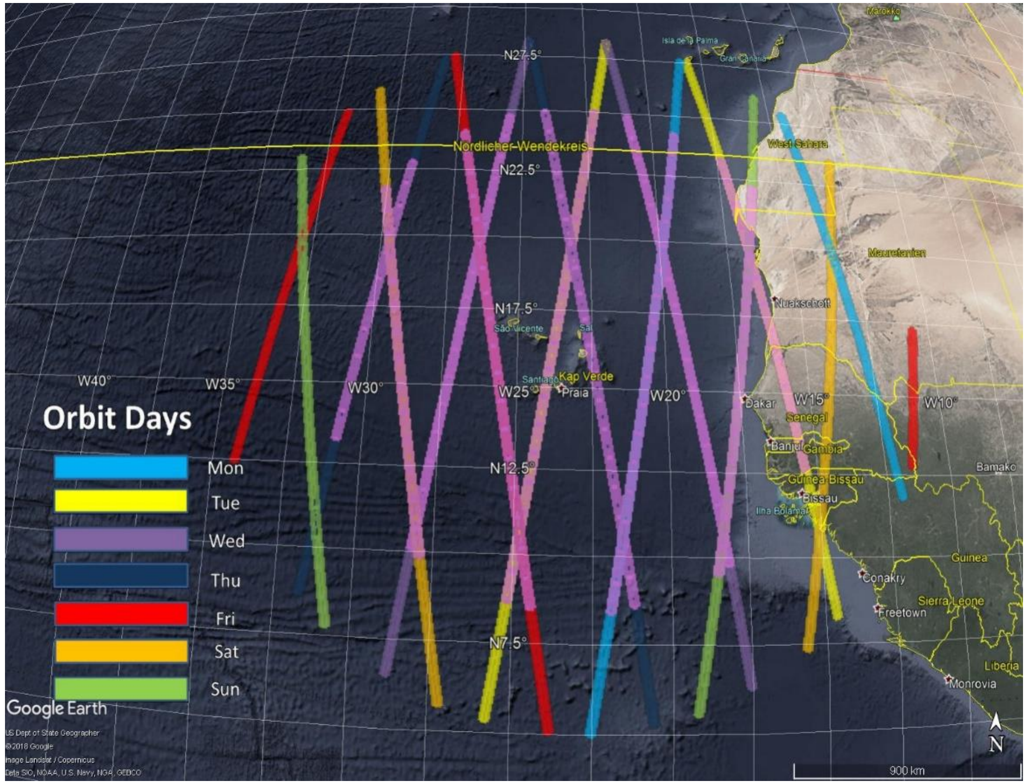
➔ Number of rejected data by QC should be included in validation results

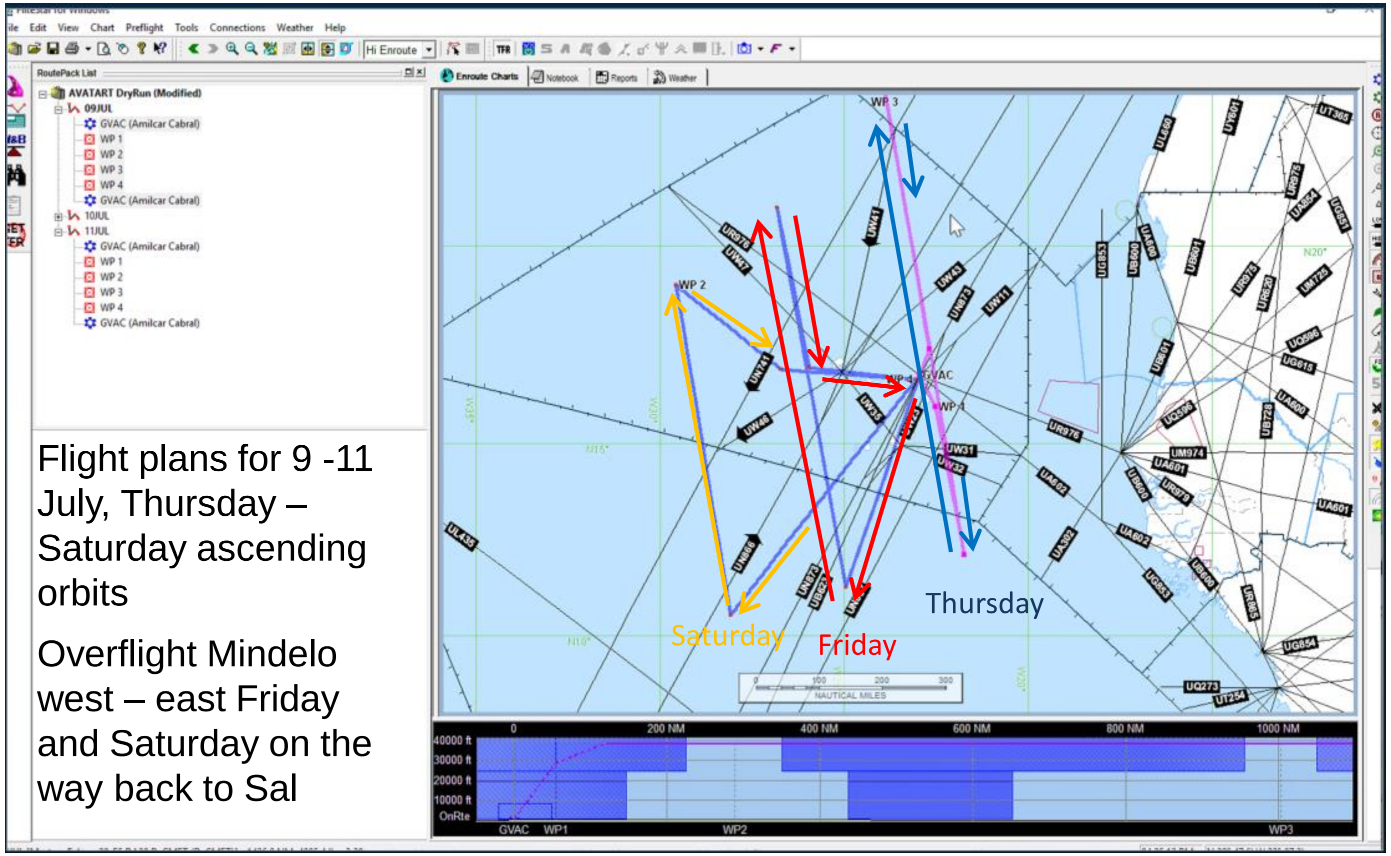
➔ QC based on est. err. in the Rayleigh wind product has to be treated with care because of its dependence of background (season/location) and algorithm baseline

➔ Alternative QC of Aeolus Rayleigh winds based on MAD suggested



Outlook – AVATAR-Tropics around Cape Verde in 2021





Flight plans for 9 -11 July, Thursday – Saturday ascending orbits

Overflight Mindelo west – east Friday and Saturday on the way back to Sal

- Participation in NASA organized dry run (55 participants, NASA, Uni Washington, LATMOS, DLR, KIT, LMU); flights planned for 9 – 11 July 2020
- Meteorological conditions with modest to strong dust events and maximum windspeeds up to 30 m/s (typically 20 m/s) in 4 km – 5 km altitude typical in regions free of high clouds. Weather stable within to the two-three days planning horizon ➔ good campaign weather
- AVATART planned for 21/06 – 15/07/2021 incl. transfer days to/from Sal ➔ Goal: Validate and subsequently improve wind, cloud and aerosol products
- Good Aeolus signal performance necessary for penetration of the beam well into and through the Saharan dust layers!

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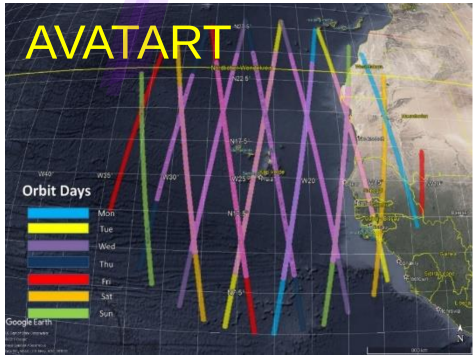
Summary and conclusions

- 20 Aeolus underflights in three campaigns with A2D and 2-µm DWLs onboard the DLR Falcon were conducted in different seasons, locations and Aeolus performance situations

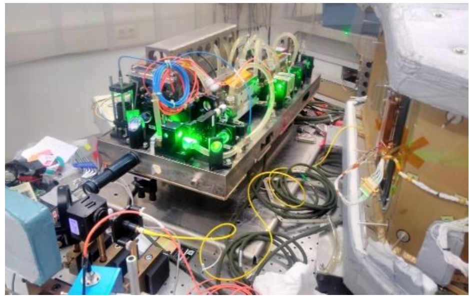
  → Airborne campaign data remains of importance throughout the mission (re-processed and –analyzed Aeolus data), covering the intermediated perspective between ground based (local) and NWP model (global) validation

- DLR tropical campaign AVATART planned for 21/06 – 15/07/2021 on Sal / Cape Verde



- The heritage of the A2D performance and development together with the 2-µm reference DWL has been and is an integral part of the Aeolus mission success

  → A2D demonstrates the potential of the technology and contributes to the Aeolus operations and algorithm optimization incl. lessons learned for a FO mission
  → Airborne validation, especially with an airborne technology demonstrator became an integral part of all planned atmospheric lidar missions



Photograph taken on the flight over the east coast of Greenland during the Aeolus underflight #5 on 16 September 2019.

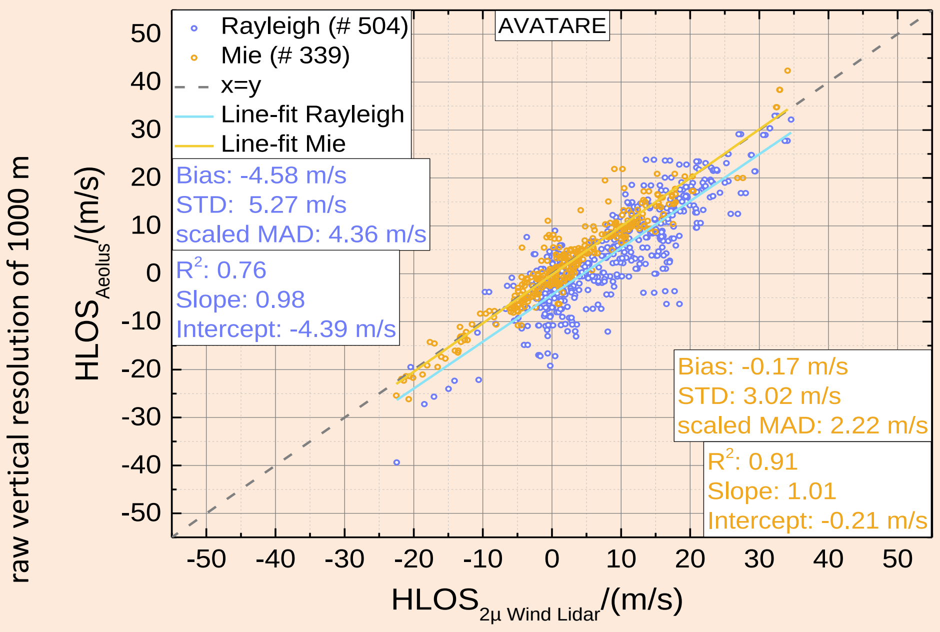
Photograph taken on the flight over the east coast of Greenland during the Aeolus underflight #5 on 16 September 2019.

Only Aeolus data with an estimated error of
< 8 m/s (Rayleigh) and
< 4 m/s (Mie) are considered.

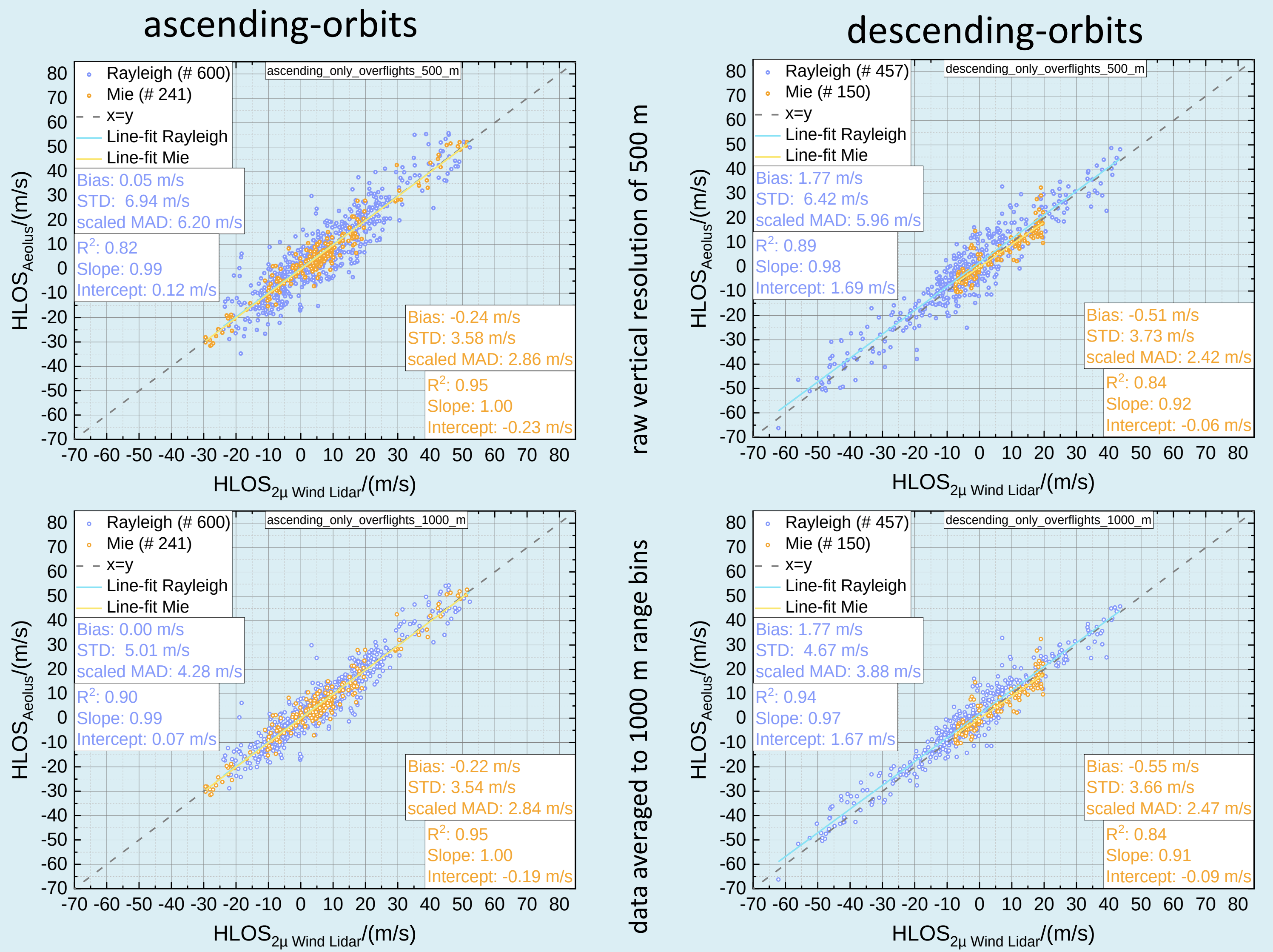
2-µm vs. Aeolus winds statistical comparison

AVATAR-E

ascending-orbits



AVATAR-I



A doubling of the signal level leads to a decrease of the Rayleigh-clear random error by √2
➔ the Rayleigh-clear wind random error is Poisson noise limited
➔ Rayleigh winds directly benefit from signal recovery

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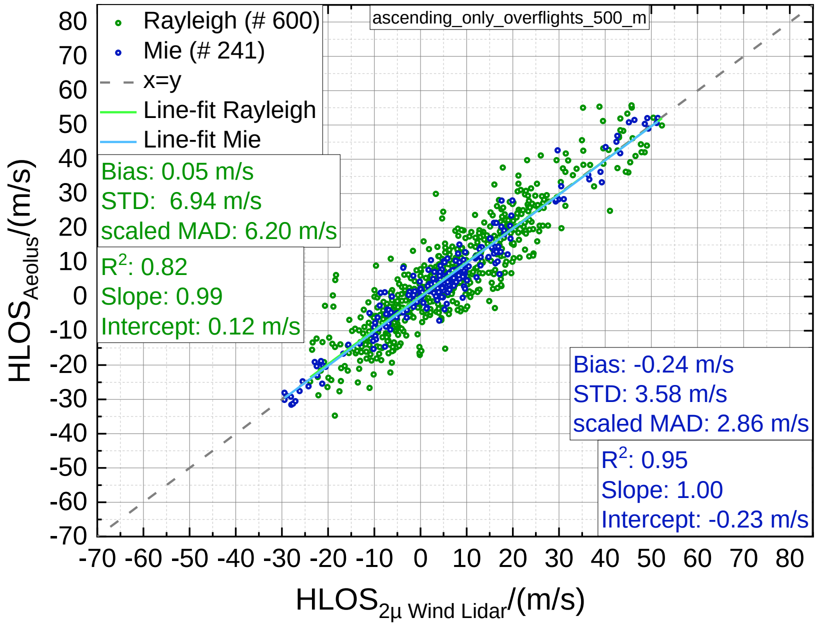
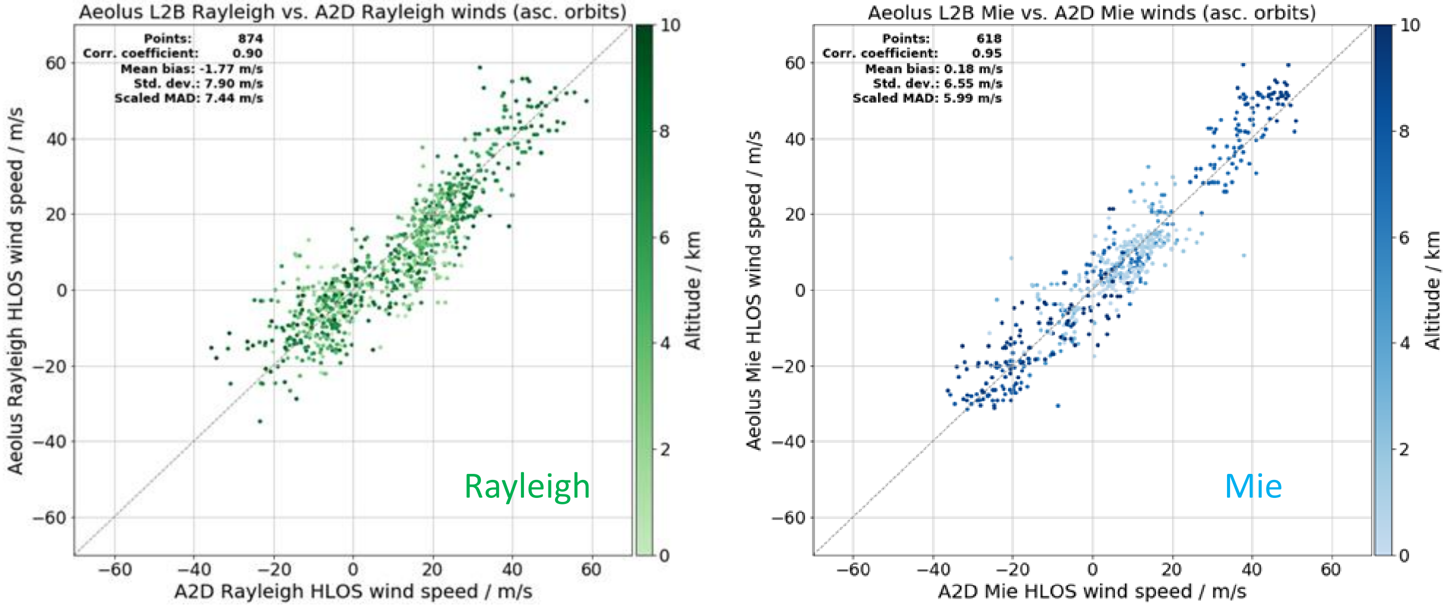
Statistical comparison of Aeolus winds vs. 2-µm DWL and A2D data from AVATARI

Ascending orbits Aeolus vs. 2-µm DWL Rayleigh and Mie winds



Ascending orbits Aeolus vs. A2D Rayleigh and Mie winds



Aeolus L2B vs.2-µm	Ascending		Descending	
	Mie	Ray	Mie	Ray
Number of compared bins	241	600	150	457
Mean bias (m/s HLOS)	-0.2	0.1	-0.5	1.8
Scaled MAD (m/s HLOS) 0.5 km	2.7	6.1	2.2	5.9
Scaled MAD (m/s HLOS) 1 km	2.7	4.2	2.3	3.8

* Aeolus random errors were corrected for the 2-µm random error of 1 m/s, 2-µm DWL observations are considered bias-free

Aeolus wind random errors for 0.5 km and 1 km range bins (2-µm DWL)

Aeolus L2B vs.A2D	Ascending		Descending	
	Mie	Ray	Mie	Ray
Number of compared bins	618	874	317	636
Mean bias* (m/s HLOS)	-0.3	-1.4	-2.4	3.6
Scaled MAD* (m/s HLOS)	4.7	5.3	3.4	5.1

* Aeolus wind errors were corrected for the A2D bias/random errors wrt. 2-µm DWL

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

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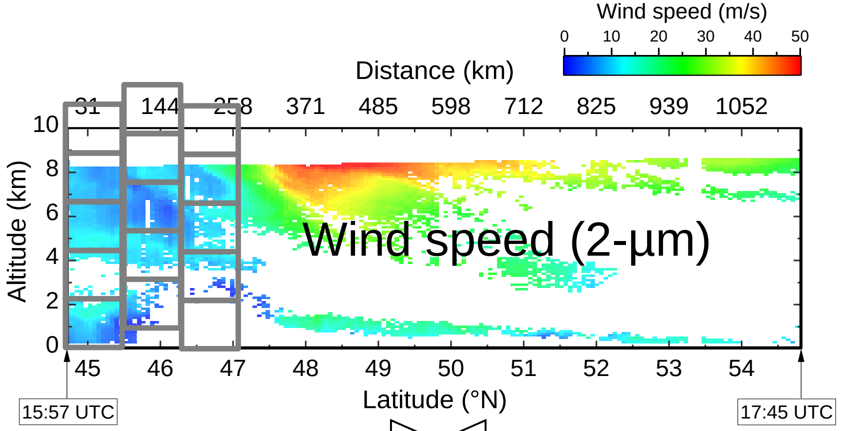
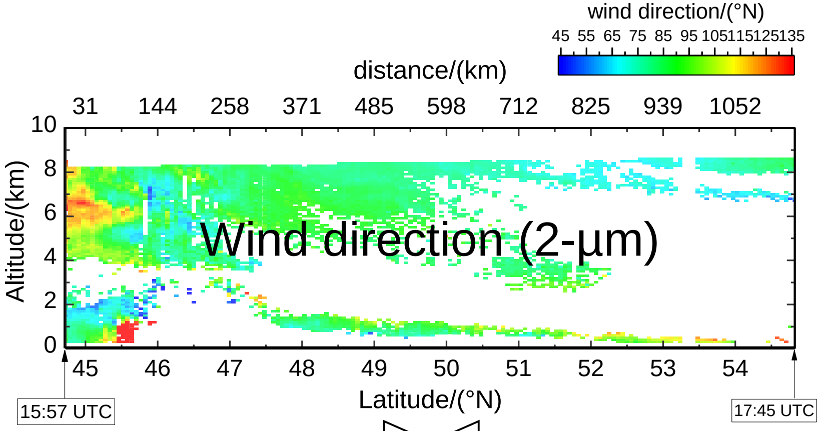
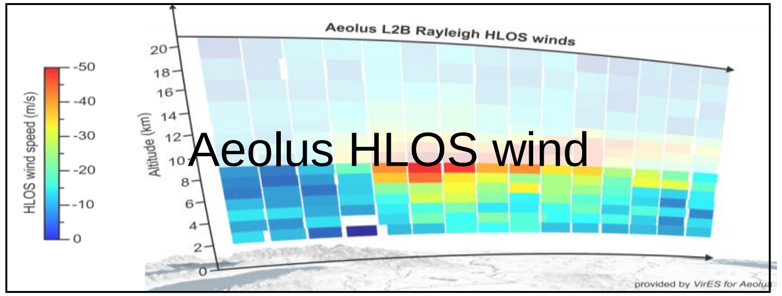
Comparison of Aeolus and 2-µm DWL data

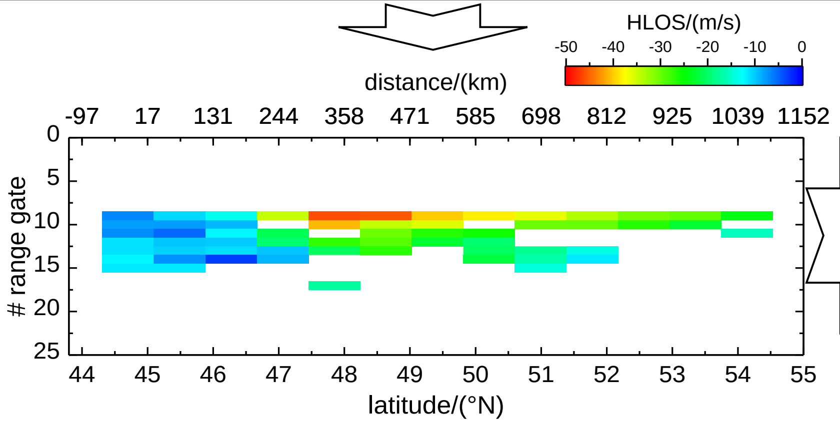




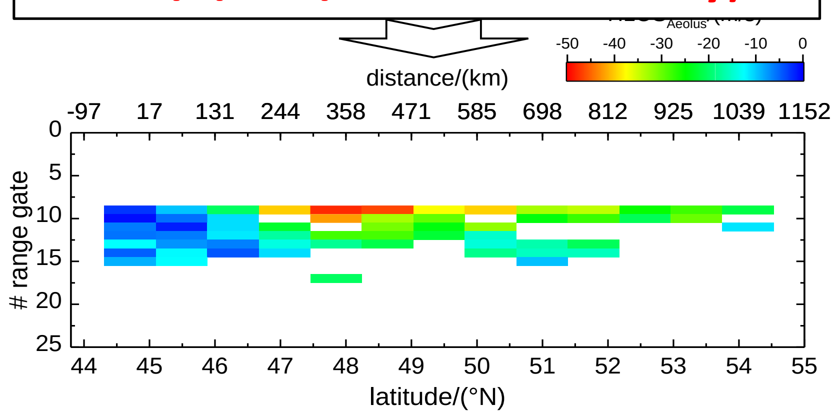


1. Averaging to Aeolus grid (**50%** data coverage as threshold)
2. projection onto the horizontal LOS

Extracting points with valid 2-µm winds **(+ est. error filter 4 m/s/8 m/s for Mie and Ray)**



Investigate the difference



- For AVATARI, Aeolus data is optionally averaged vertically (to 1000 m range bins)

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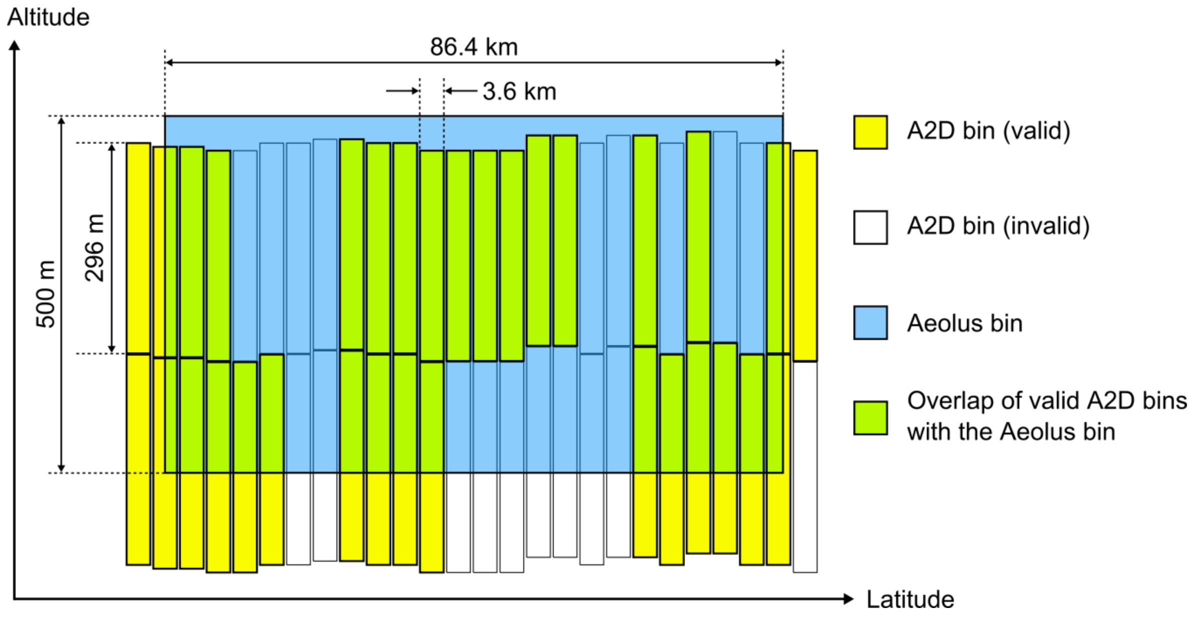
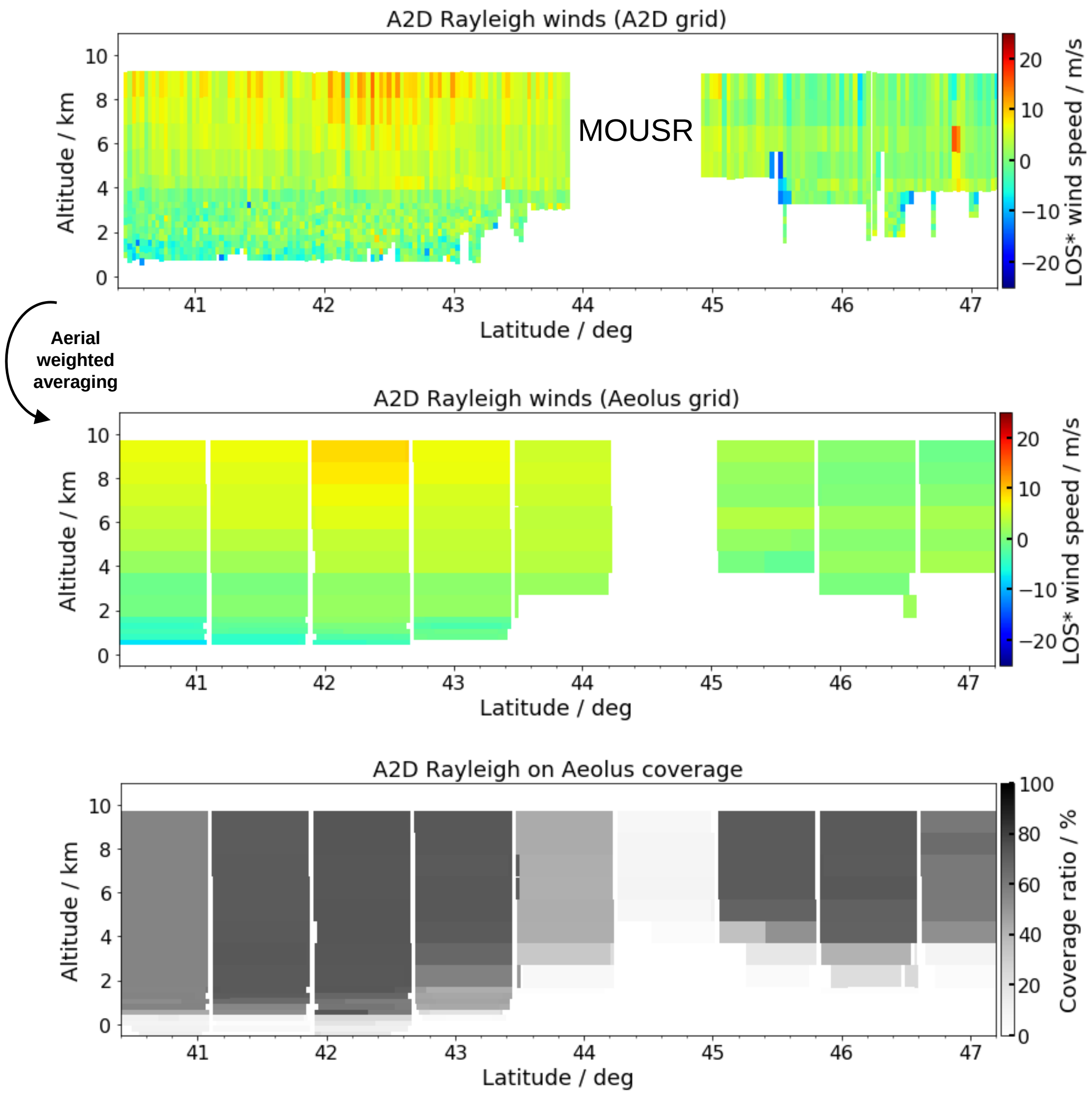
Adaptation of A2D wind results to Aeolus measurement grid





- *Aerial weighted averaging algorithm**: each valid A2D range bin covering an Aeolus range bin is allocated horizontal and vertical weights depending on the size of the contribution of the respective A2D bin to the total area of the Aeolus bin
- Coverage ratio (coverage of an Aeolus range bin by valid A2D bins) is calculated as a measure of the representativity of A2D winds within an Aeolus range bin and used as a QC parameter

**Marksteiner et al., Proc. SPIE, 8182, 81820J (2011).*

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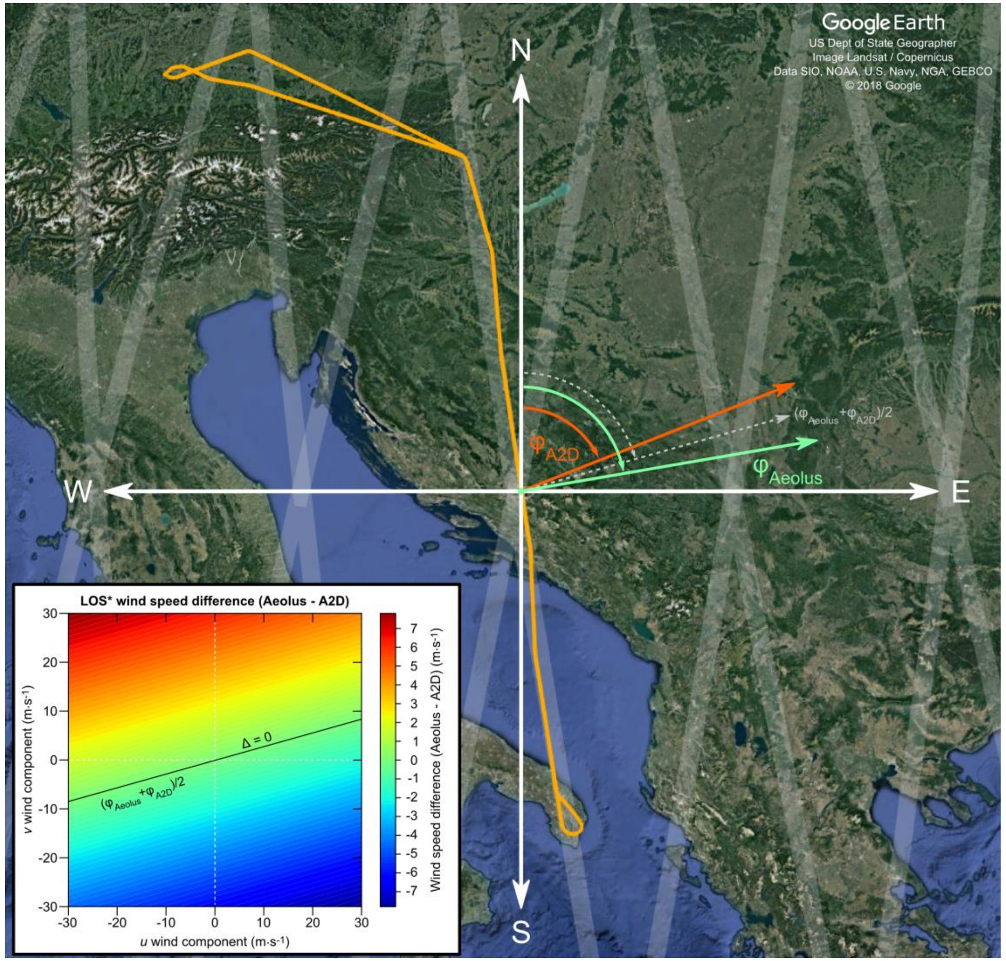
Consideration of different azimuth angles and averaging onto Aeolus grid

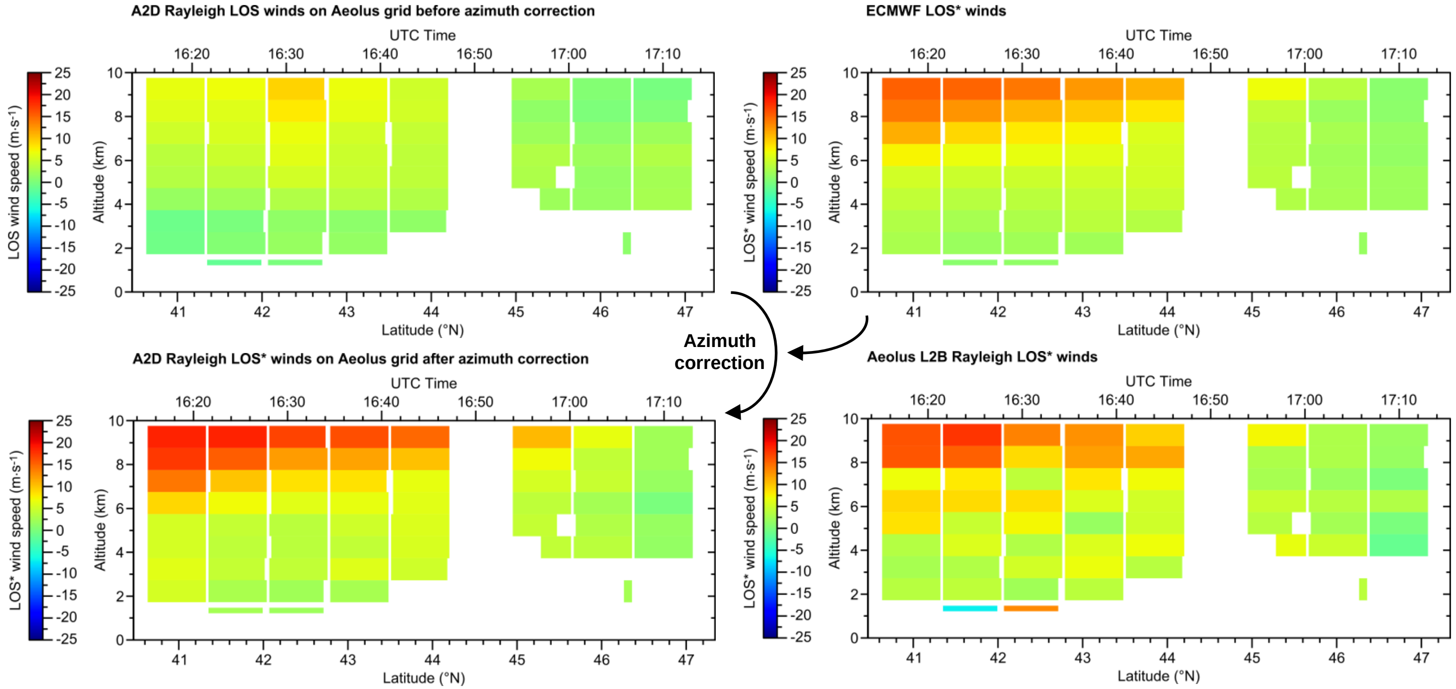
A2D and Aeolus azimuth angles during the Aeolus underflight on 22/11/2018 (WindVal III campaign)



$$v'_{\mathrm{A2D}} = v_{\mathrm{A2D}} + \Delta$$

$$\Delta = [\cos(\varphi_{\mathrm{A2D}}) - \cos(\varphi_{\mathrm{Aeolus}})] \cdot v + [\sin(\varphi_{\mathrm{A2D}}) - \sin(\varphi_{\mathrm{Aeolus}})] \cdot u$$

$\approx 68°$ $\approx 260°$ from model (L2C)

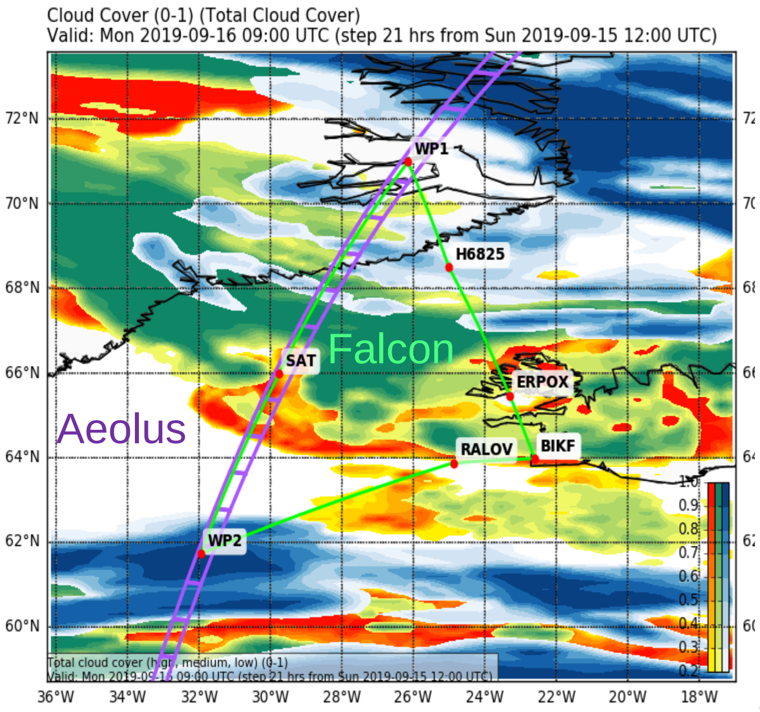


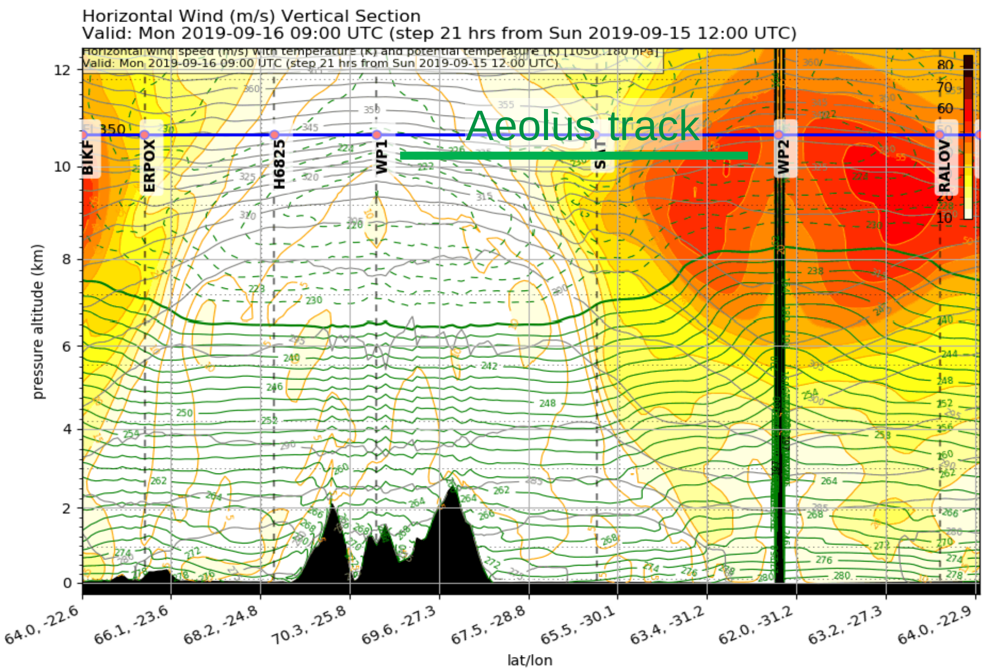
$$\text{A2D LOS} \xrightarrow[\approx 0.34]{:\sin(\theta_{\mathrm{A2D}})} \text{A2D HLOS} \xrightarrow[\text{correction}]{\text{azimuth}} \text{A2D HLOS*} \xrightarrow[\approx 0.60]{\cdot \sin(\theta_{\mathrm{Aeolus}})} \text{A2D LOS*}$$

- For azimuth correction A2D winds are converted to those winds that would have been measured along the Aeolus LOS using ECMWF model data from the L2C product

Lux et al., AMT 13, 2075 (2020)

AVATAR-I example: North Atlantic Jet Stream east of Greenland on 16/09/2019





- 1030 km long flight leg with strong horizontal and vertical wind speed gradients (0 – 50 m/s) transecting the North Atlantic jet stream along an *descending Aeolus orbit* along the Greenland east coast (71.0°N, 26.2°W to 61.7°N, 32.0°W)
- Aeolus covered the track between 08:38:33 UTC and 08:40:58 UTC, while the Falcon flew from 07:56 UTC to 09:18 UTC
- Cloud-free conditions and mid-level clouds in most parts of the targeted area, high-level clouds in the southernmost part

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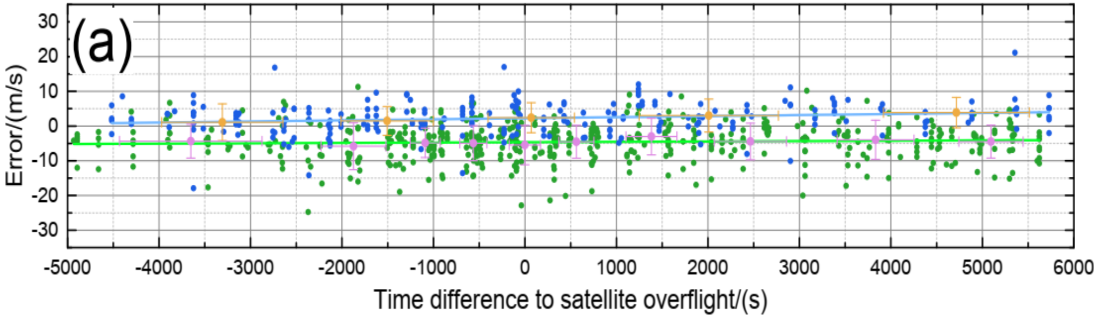
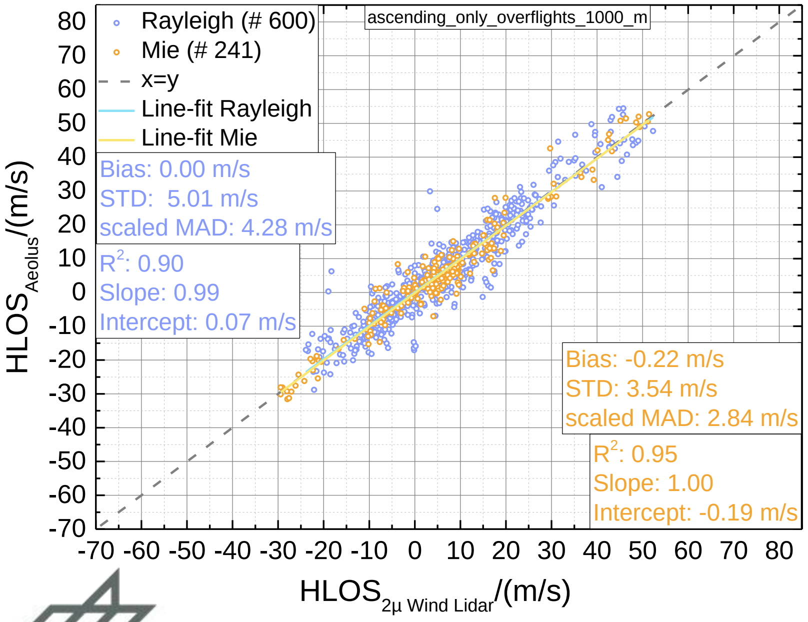
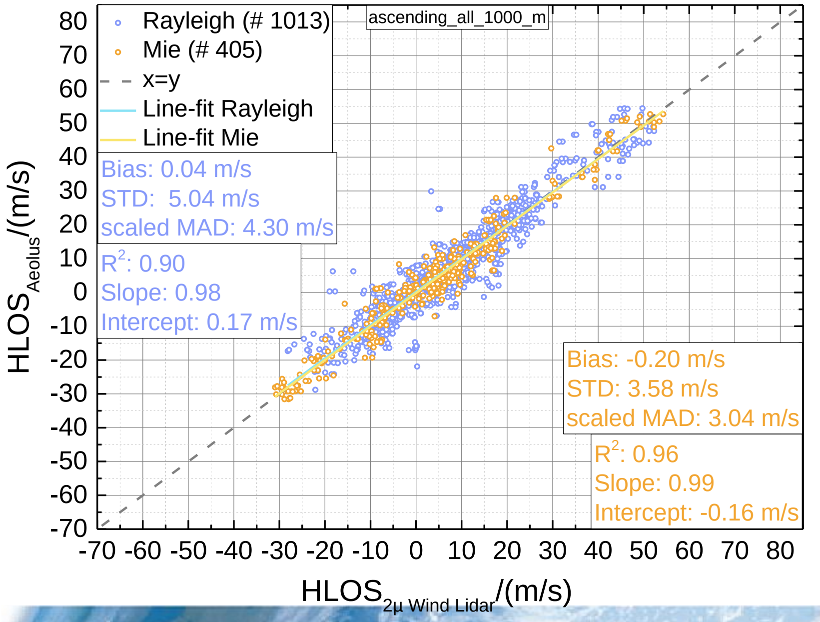
Statistical comparison of Aeolus and 2-µm Lidar data

Impact of the temporal distance on the comparison

- For WindVal III and AVATARE, all 2- µm DWL data available from the underflight region (forth and back flight legs) have been used for statistical comparison [1]
  → It was shown that the temporal difference of ±1.5 hours had no significant impact on the systematic error
  → principally depending on the atmospheric dynamical situation → verification for AVATARI data





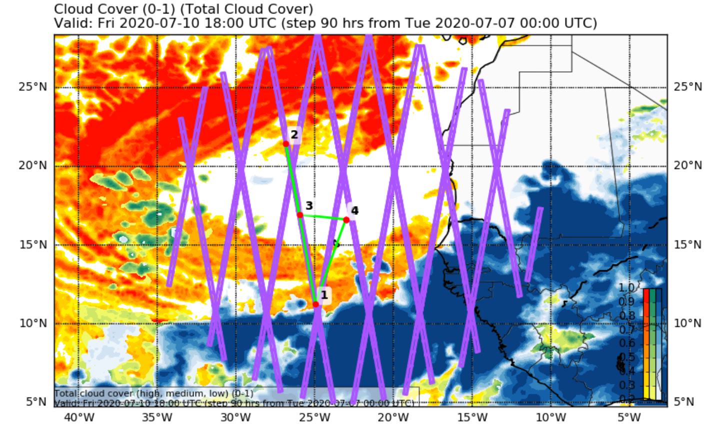


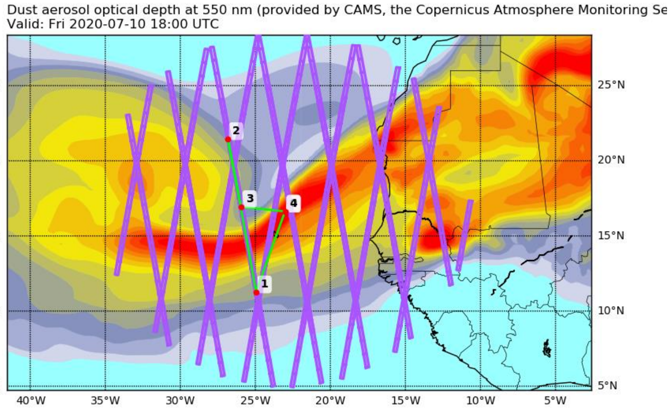
- Number of available data points reduce from **1013** to **600** (Rayleigh) and from **405** to **241** (Mie)
- **All parameters** retrieved from the statistical comparison (bias, STD, s. MAD, slope, intercept) for both Rayleigh and Mie winds **remain similar**

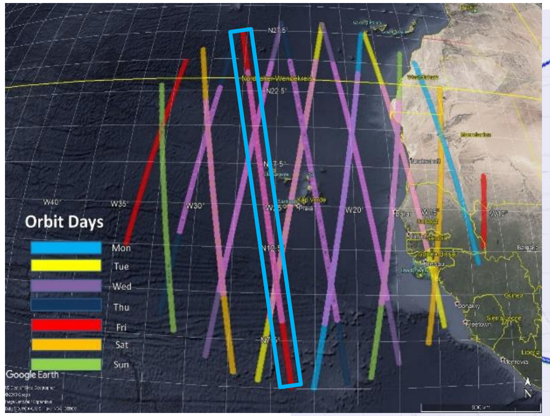
→ **As enough data points are available for comparison, only flight leg data with respective overpasses are used in the following**

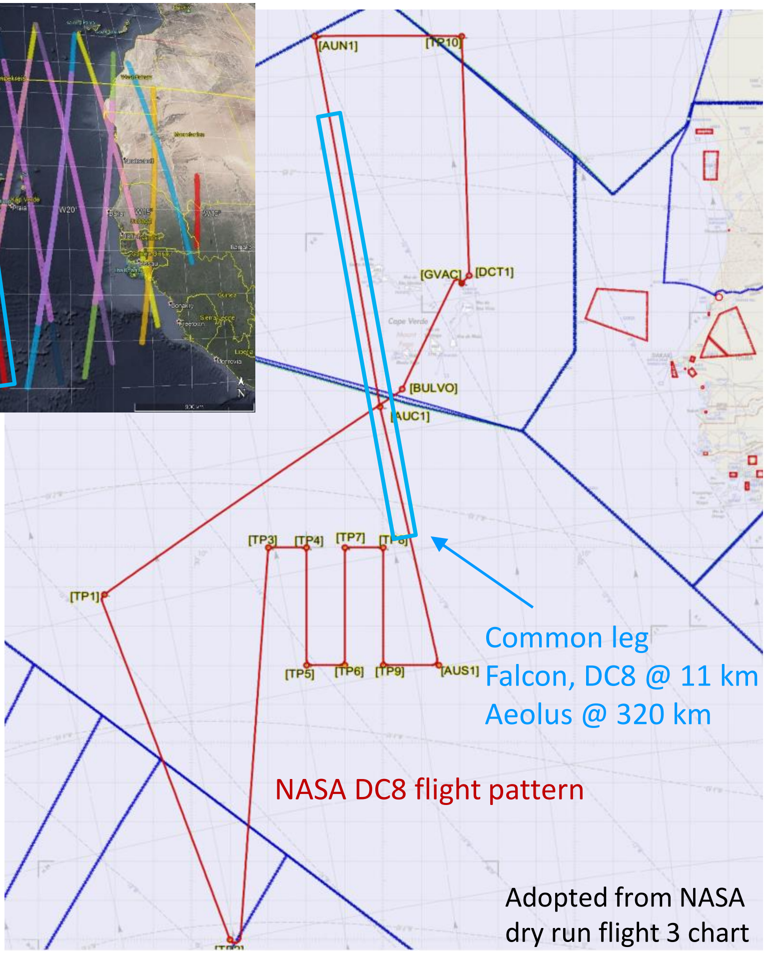
[1] Witschas et al., 2020, AMTD

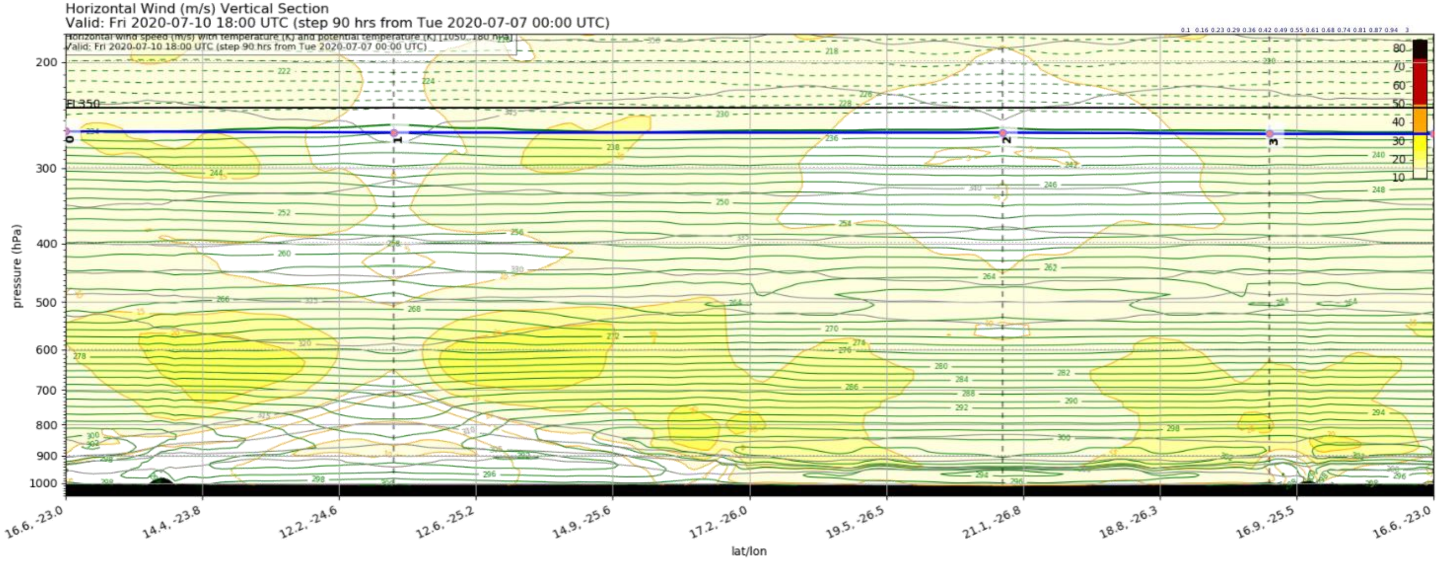
AVATART Dry Run Example Friday 10 July 2020





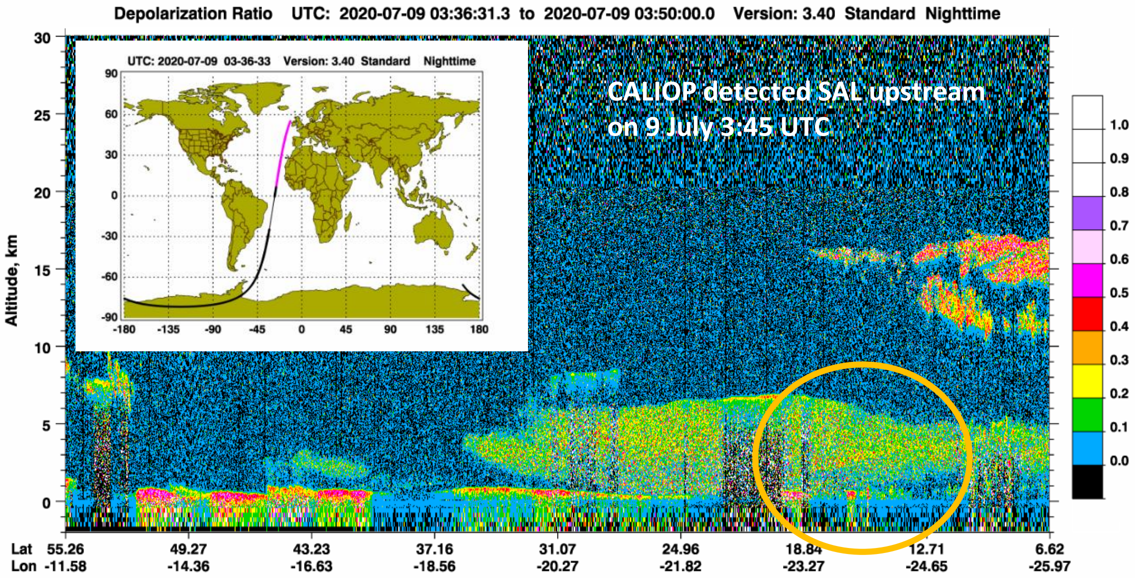


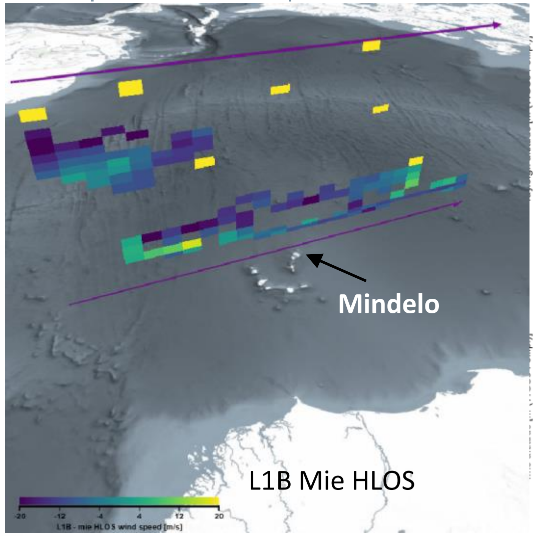


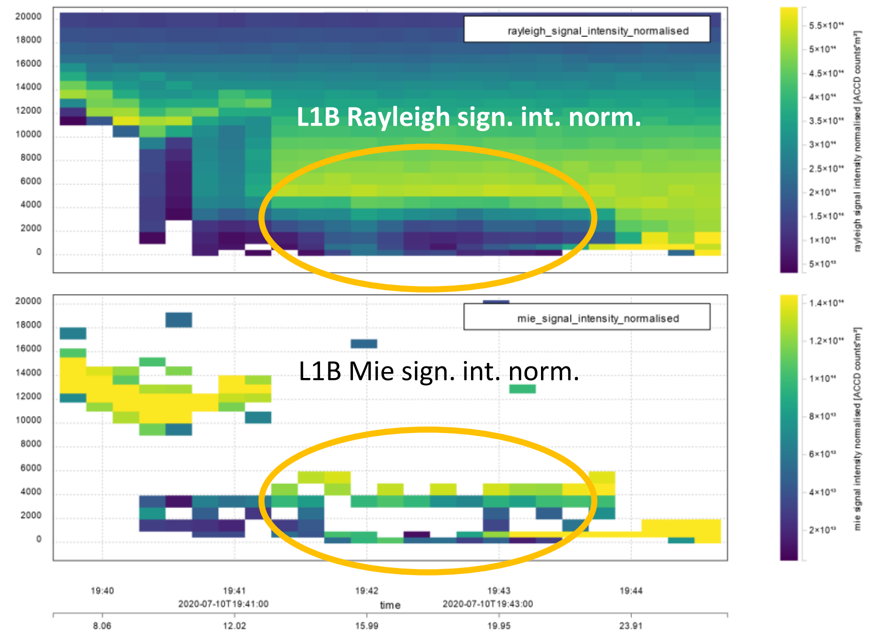


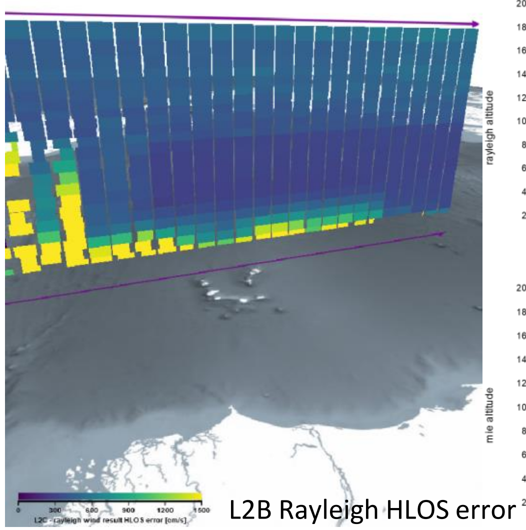
- ITCZ within reach but high clouds allow useful comparison only around the northern edge with the Falcon (WP1)
- Flight planning approach based on previously used forecast tools proved to work well also for AVATART
- CALIOP expedited browse images as quick look useful but 3 days delayed

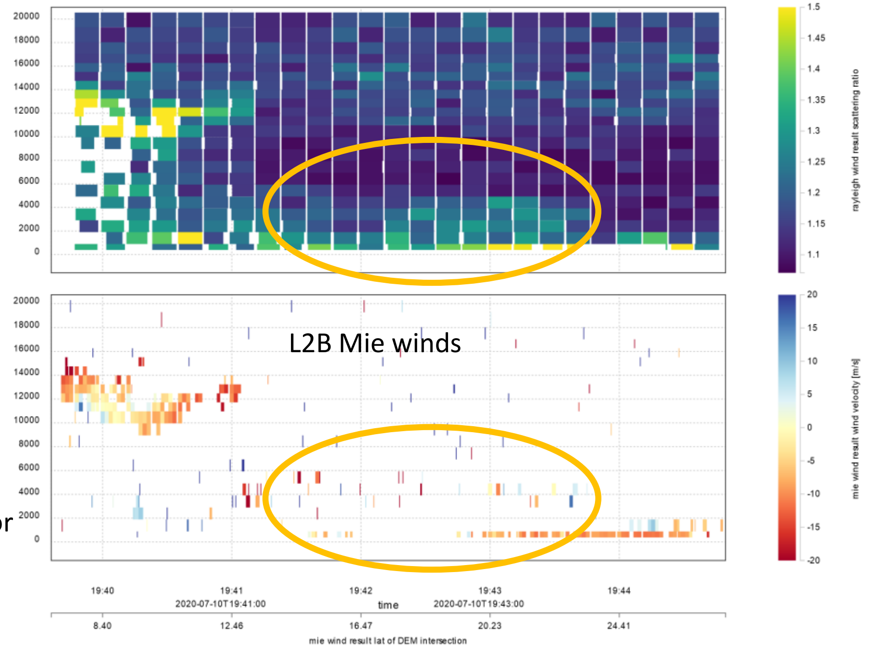
Aeolus and CALIOP observations on Friday 10 July 2020









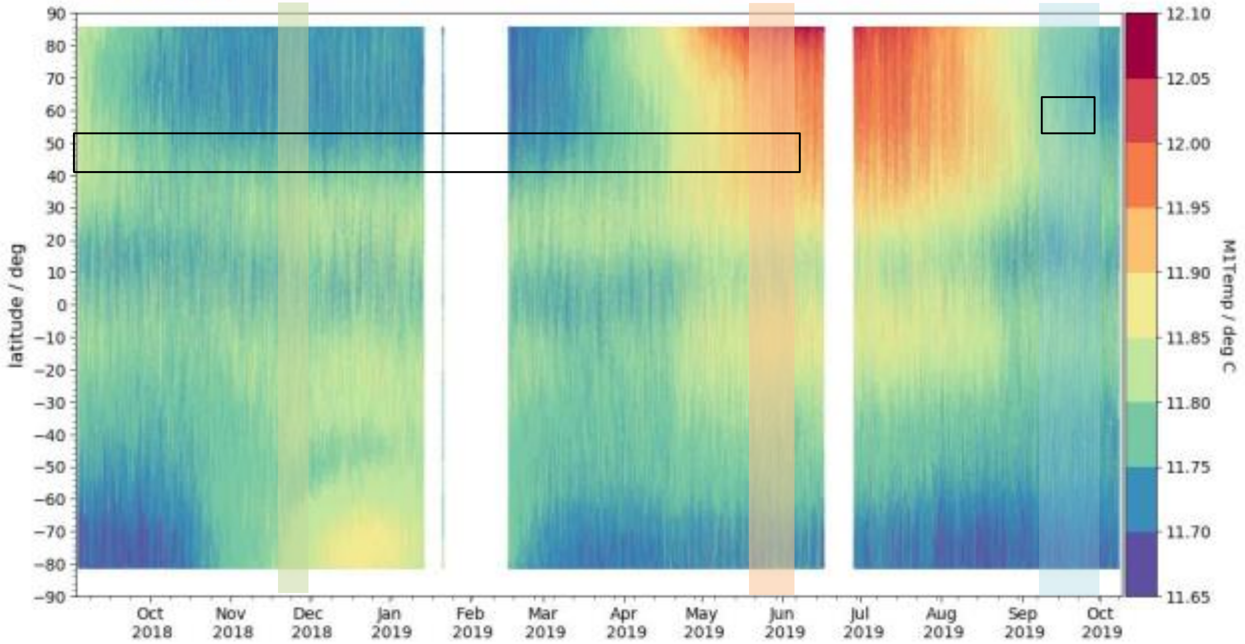


- CALIOP lets expect a dust layer in 2 – 5 km altitude which is seen most clearly in strong Rayleigh signal attenuation
- Only few of the L1B/L2 B Mie winds (obs. level) are valid L2B Mie winds inside the dust layer, despite scattering ratio between 1.2 and 1.3 in SAL

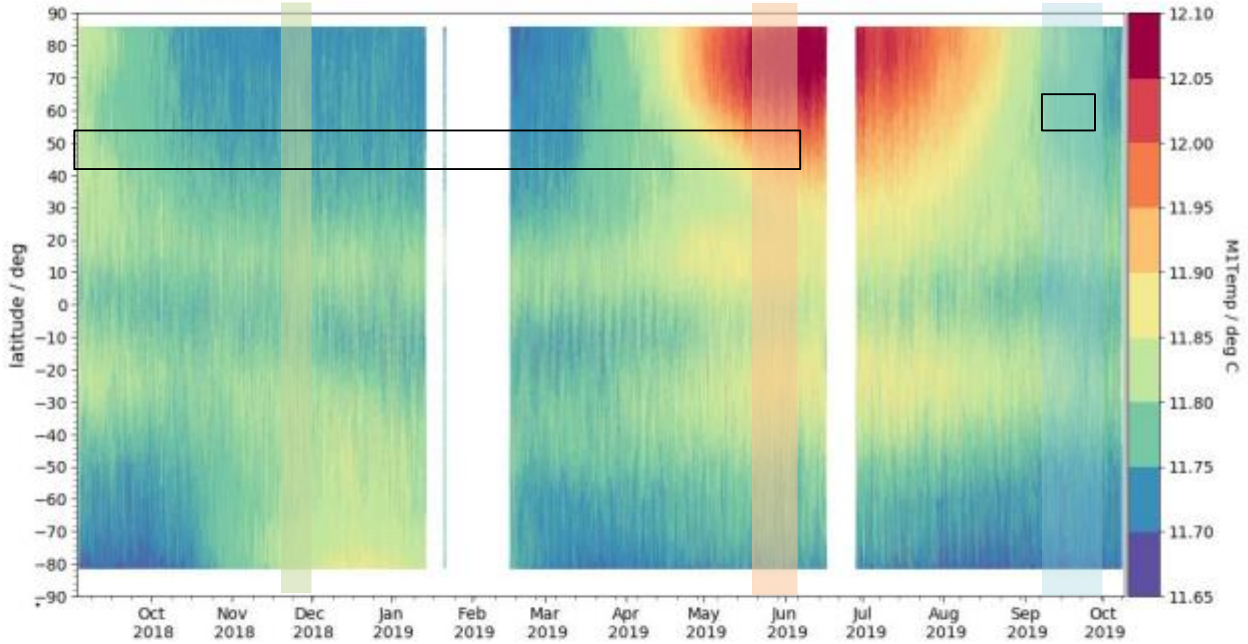
Aeolus Telescope M1 Temperature Variations

Hovmöller diagrams

ascending



descending



WindVal-III 2018
17/11 – 05/12

AVATARE 2019
24/05 – 05/06

AVATARI 2019
09/09 – 01/10

Courtesy Fabian Weiler
DISC WM061