19 to 20 February 2025, NOAA Center for Weather and Climate Prediction (NCWCP), College Park, MD

Workshop on Space-based Measurements of 3-Dimensional Winds
20 February 2025

AEOLUS VALIDATION WITH THE DLR AIRBORNE DOPPLER WIND LIDARS: 2-µm HETERODYNE DETECTION AND 355 nm ALADIN AIRBORNE DEMONSTRATOR

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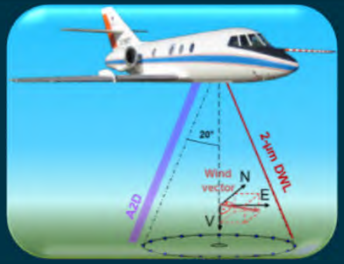
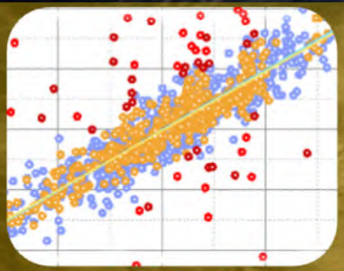
Outline – Status and Overview



➢ AIRBORNE DOPPLER WIND LIDARS

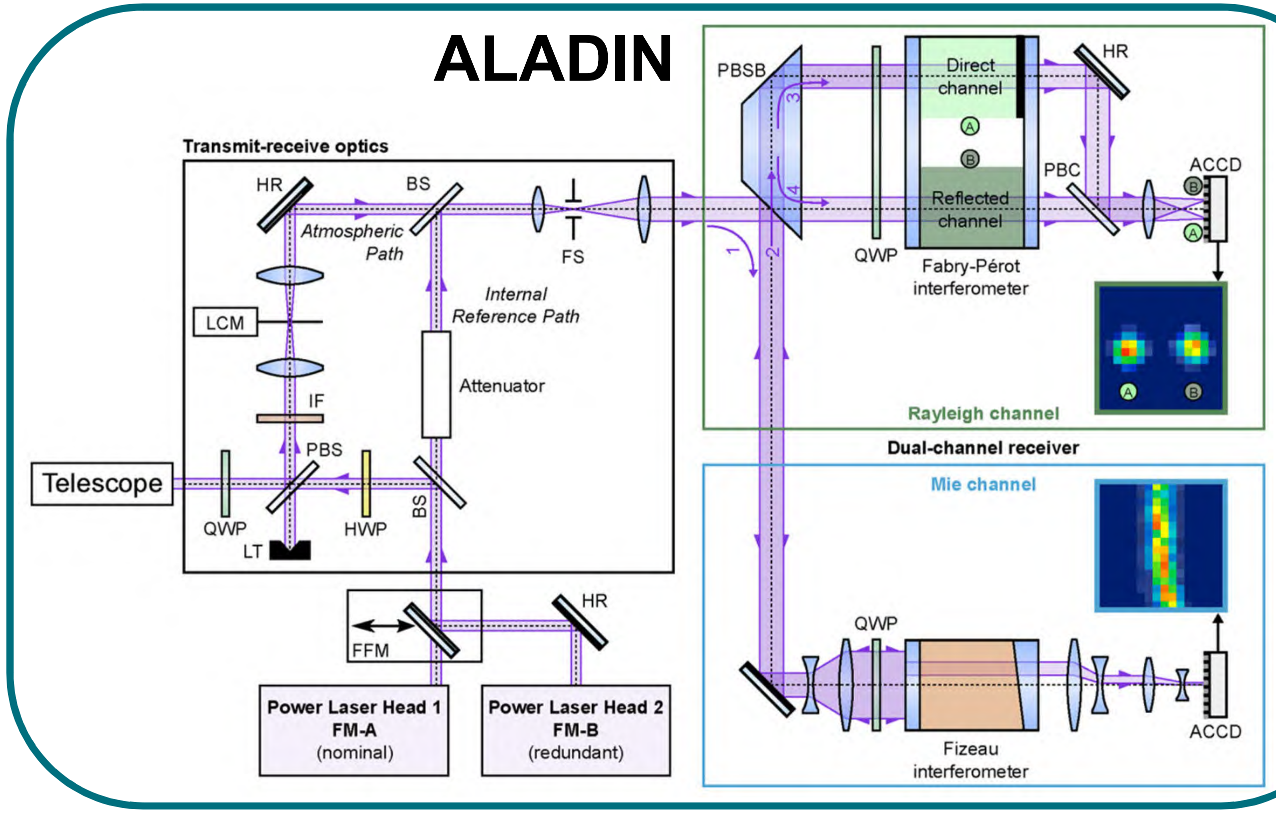
➢ AEOLUS VALIDATION CAMPAIGNS

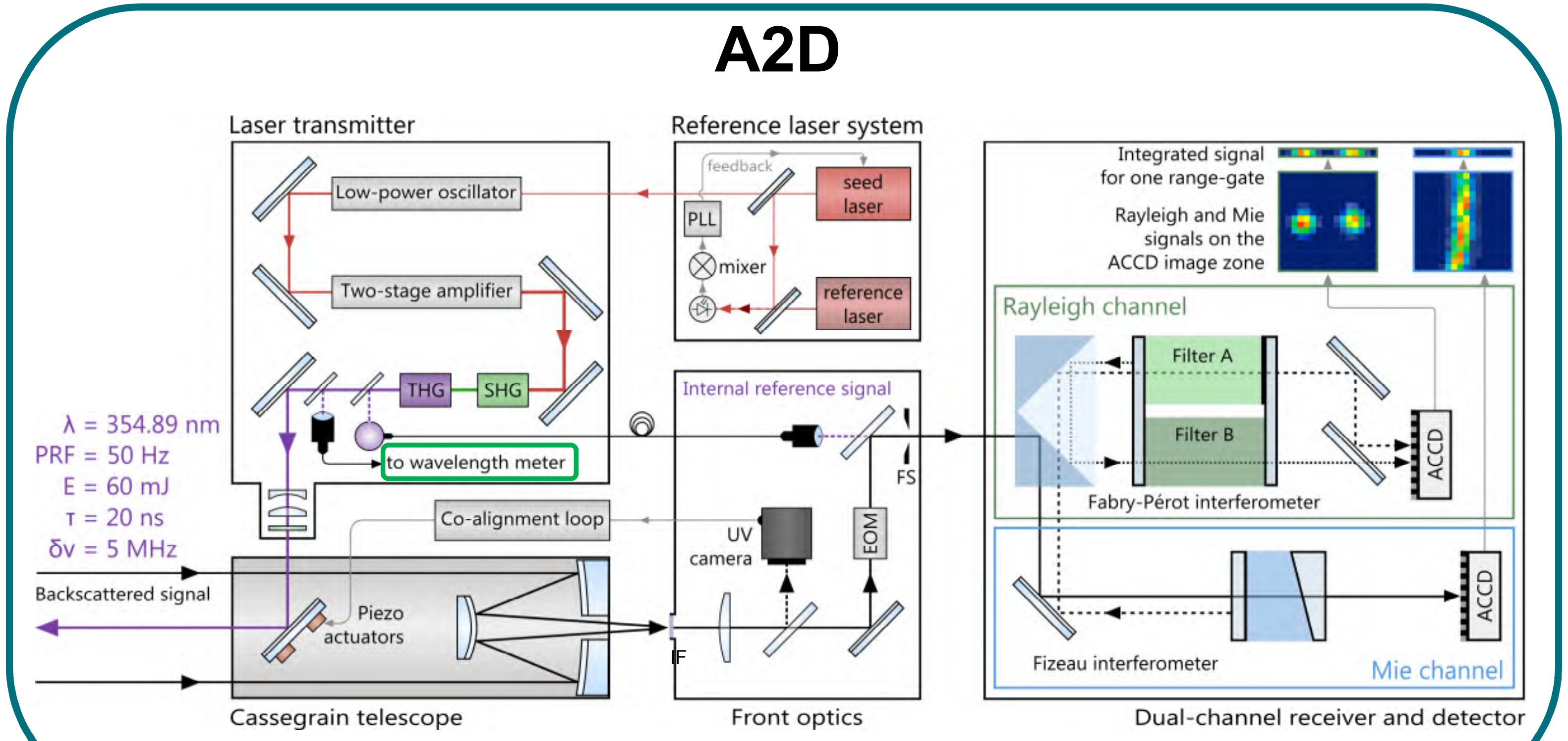


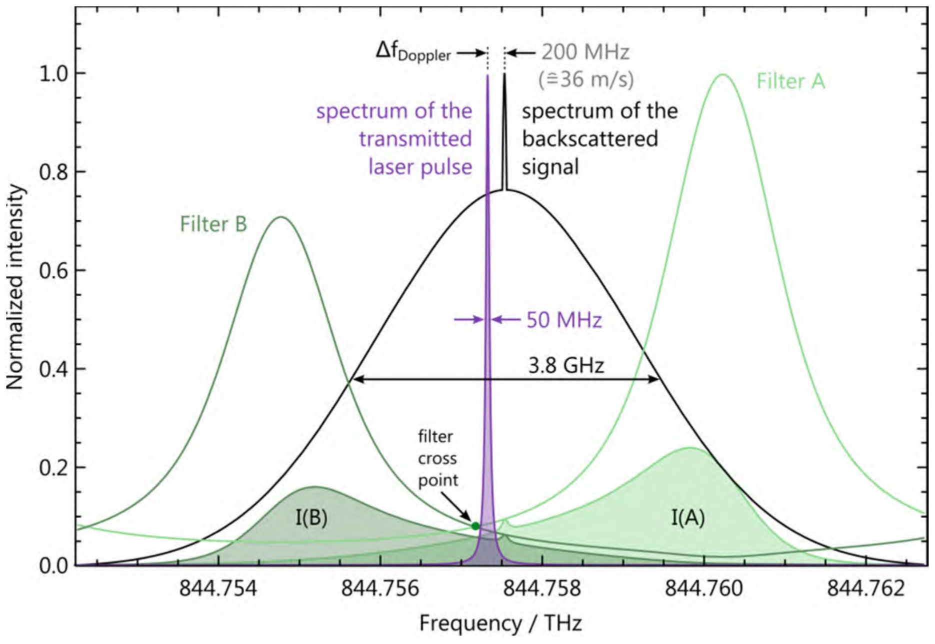
➢ VALIDATION RESULTS

➢ SUMMARY AND OUTLOOK

ALADIN on Aeolus and the Airborne Demonstrator (A2D)



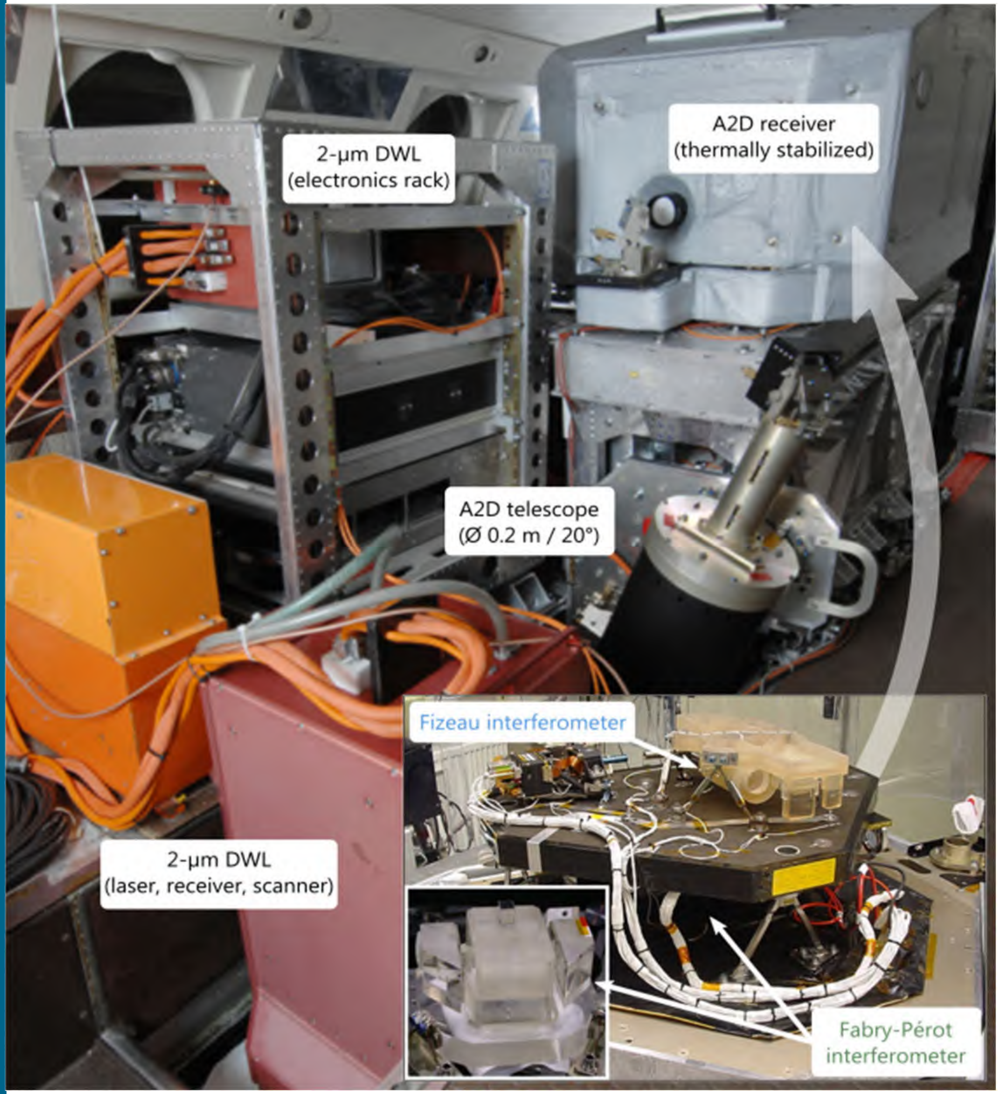




Measurement principle (example backscatter spectrum with scattering ratio ~1.01)

Parameter	ALADIN	ALADIN Airborne Demonstrator (A2D)
Laser wavelength	354.8 nm	354.9 nm
Repetition rate	50.5 Hz	50 Hz
Pulse energy	53…90 mJ	60 mJ
Linewidth	50 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

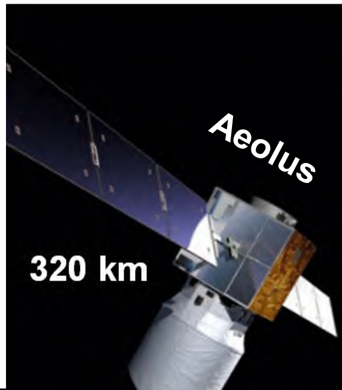
A2D and the 2-µm Doppler Wind Lidars (DWLs)

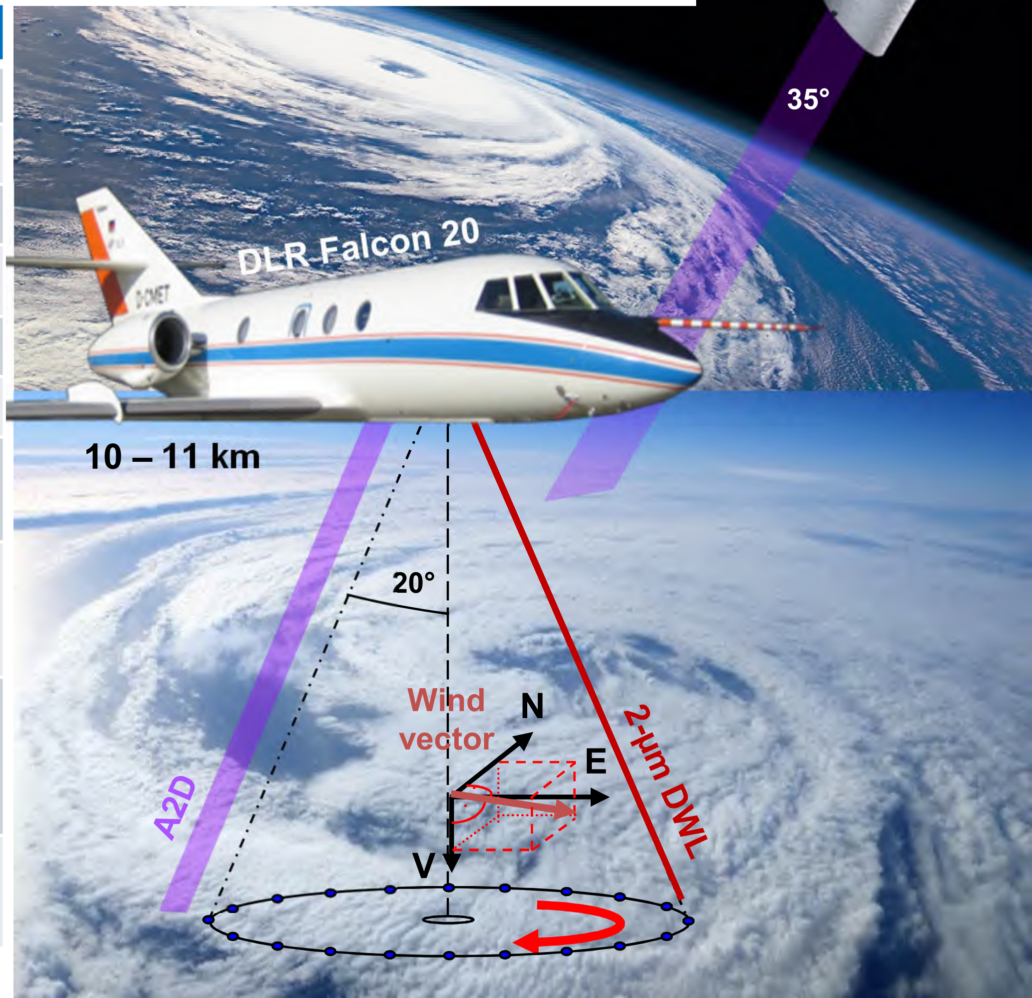


- The ***A2D (ALADIN Airborne Demonstrator)*** was built as a **suborbital-twin** featuring a high **technological commonality with** the **Aeolus lidar** (ALADIN)
- **A2D was operated** for measurements from ground and on the aircraft **together with the scanning heterodyne-detection *2-µm DWL*** which provided reference profiles of **wind speed and direction**
- Already for the **Aeolus mission preparation**, both DWLs were deployed for **international airborne campaigns** to **validate the ALADIN concept** with atmospheric signal, and to support the algorithms development

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 $m \cdot s^{-1}$ = 720 km/h = 12 km/min.	3.6 km (18 s)	0.2 km LOS, 8.4 km scan
Precision (random error)	1.5 $m \cdot s^{-1}$ (Mie)* 1.8 $m \cdot s^{-1}$ (Rayleigh)*	< 1 $m \cdot s^{-1}$

*on line of sight (LOS)





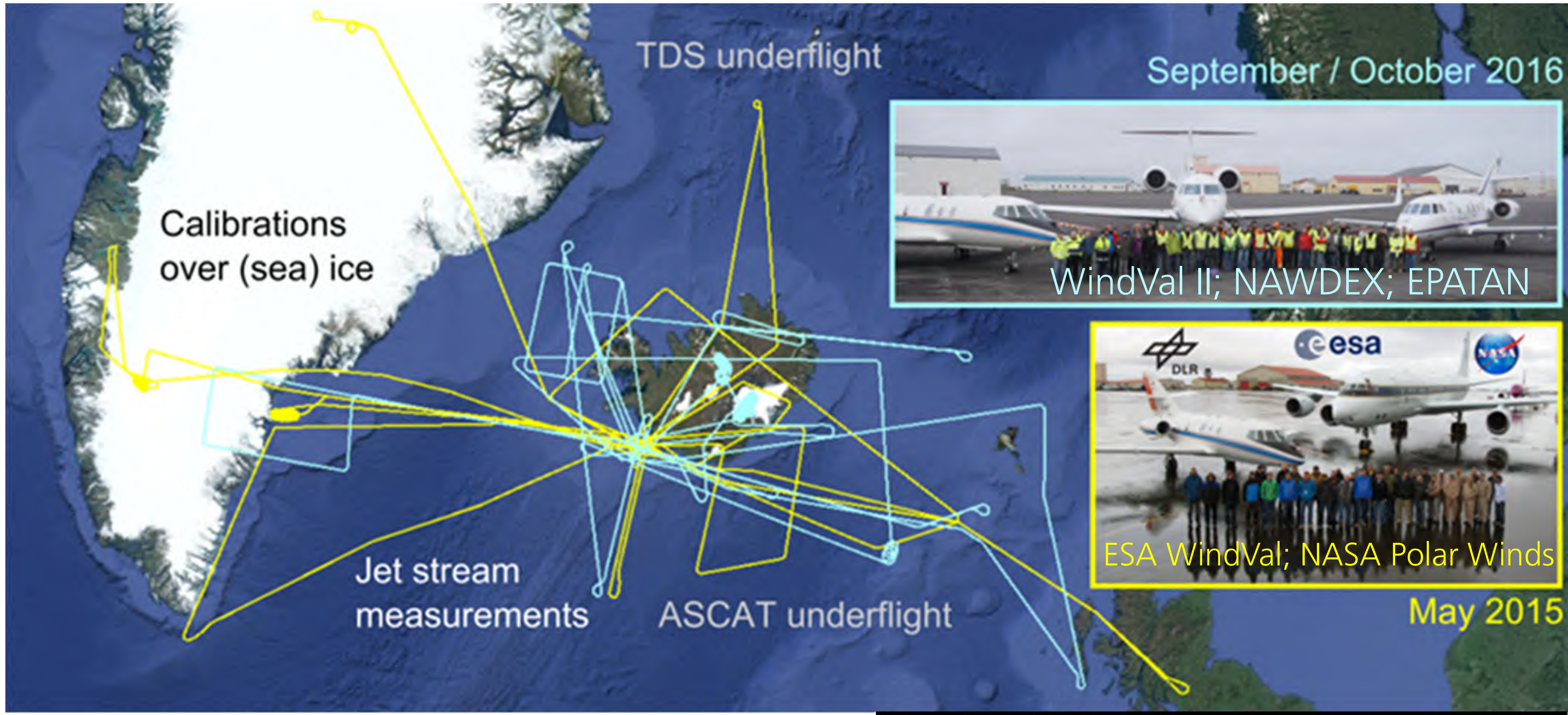
References: Reitebuch et al. (2009), **JAOT**; Lemmerz et al. (2017), **Applied Optics**; Lux et al. (2018), **AMT**; Marksteiner et al. (2018), **Remote Sensing**; Witschas et al. (2017), **JAOT**; Witschas et al. (2020), **AMT**; Lux et al. (2022), **AMT,** Lemmerz et al. (2023), **SPIE-ICSO**

Examples for International Pre-launch Airborne Campaigns (DLR/ESA/NASA/CNES)

The **A2D** was deployed on the DLR Falcon research aircraft **together with the scanning 2-µm DWL reference lidar,** to **test mission procedures and algorithms for Aeolus in-flight** (e.g. 2 campaigns in Iceland, 2015/16)

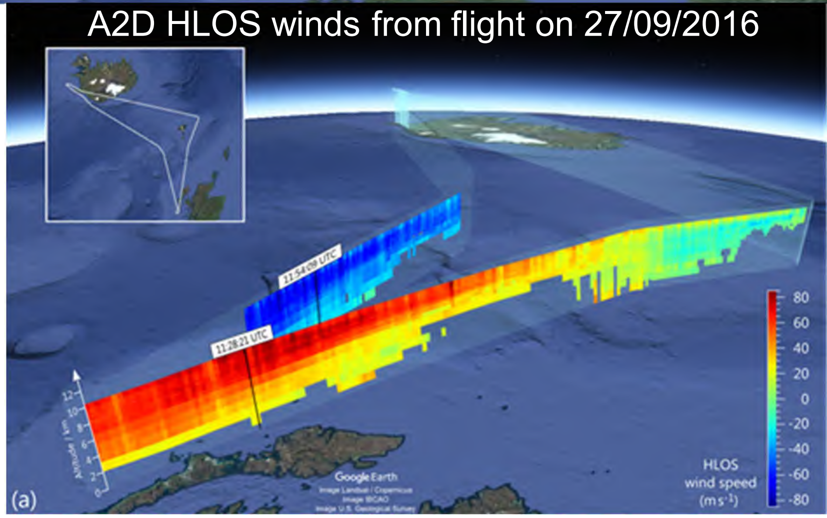
➔ Complements instrument tests by ESA and industry

➔ Delivers input for the development of wind and aerosol products



✓ **Demonstrated:** Aeolus measurement principle works reliably also in harsh airborne environmental conditions

✓ **More than 150 recommendations for the Aeolus mission derived before launch** covering instrument alignment, operations, retrieval algorithms and calibration/validation



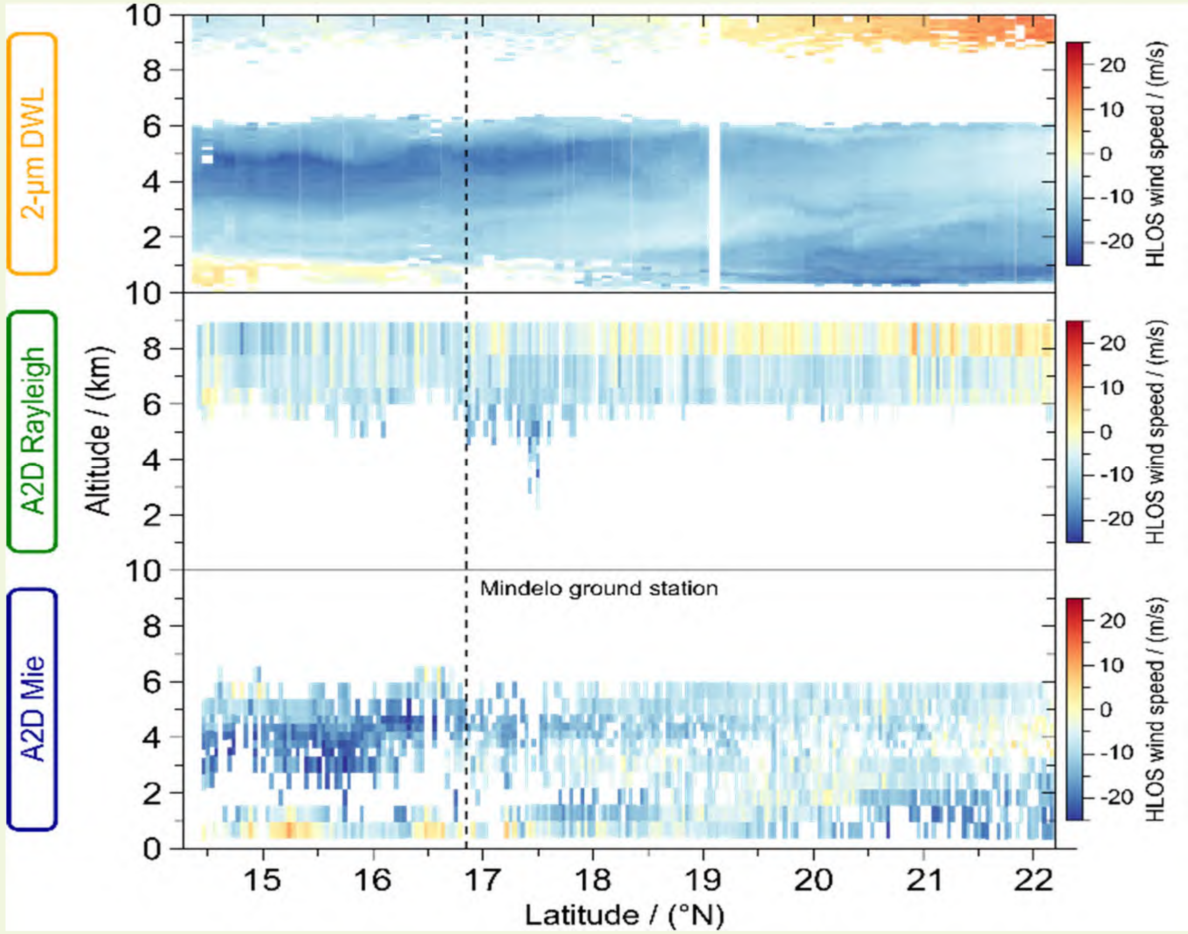
Lux et al. (2018), ***AMT***
Marksteiner et al. (2018), ***Remote Sens.***

Aeolus Airborne Validation Goals – Example Cape Verde

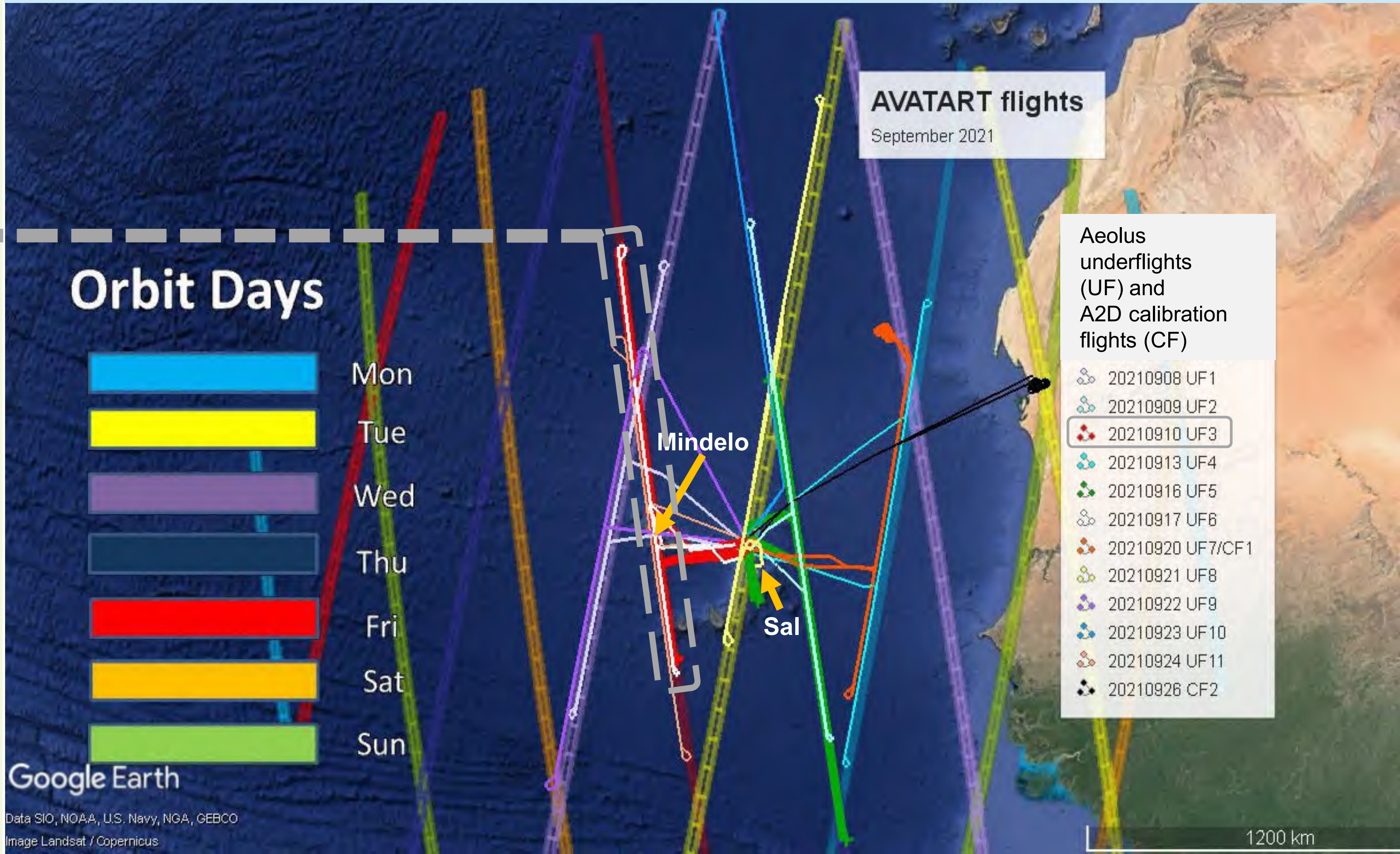
- ➔ **Characterization of the Aeolus wind products (on horizontal line-of-sight, HLOS) with parallel collocated measurements along the Aeolus track** (wind, clouds, aerosol information with higher accuracy/precision and vert./hor. resolution)
- ➔ **Support of the Aeolus processor evolution within DISC, validation of reprocessed data, and the Cal/Val community**

Synergy Direct- and Heterodyne-Detection DWL

(example *10/September/2021*)



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



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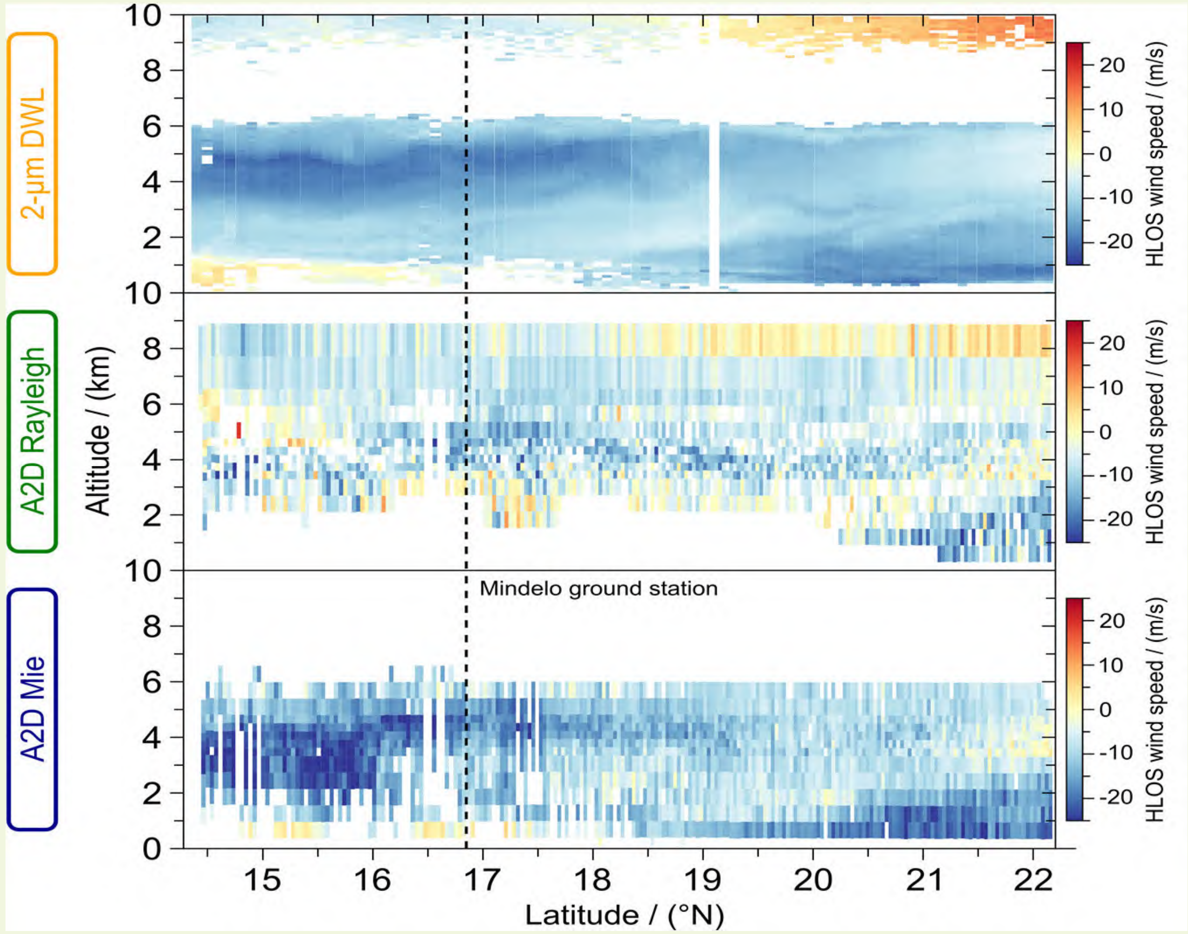
(example *10/September/2021, A2D processor evolution*)



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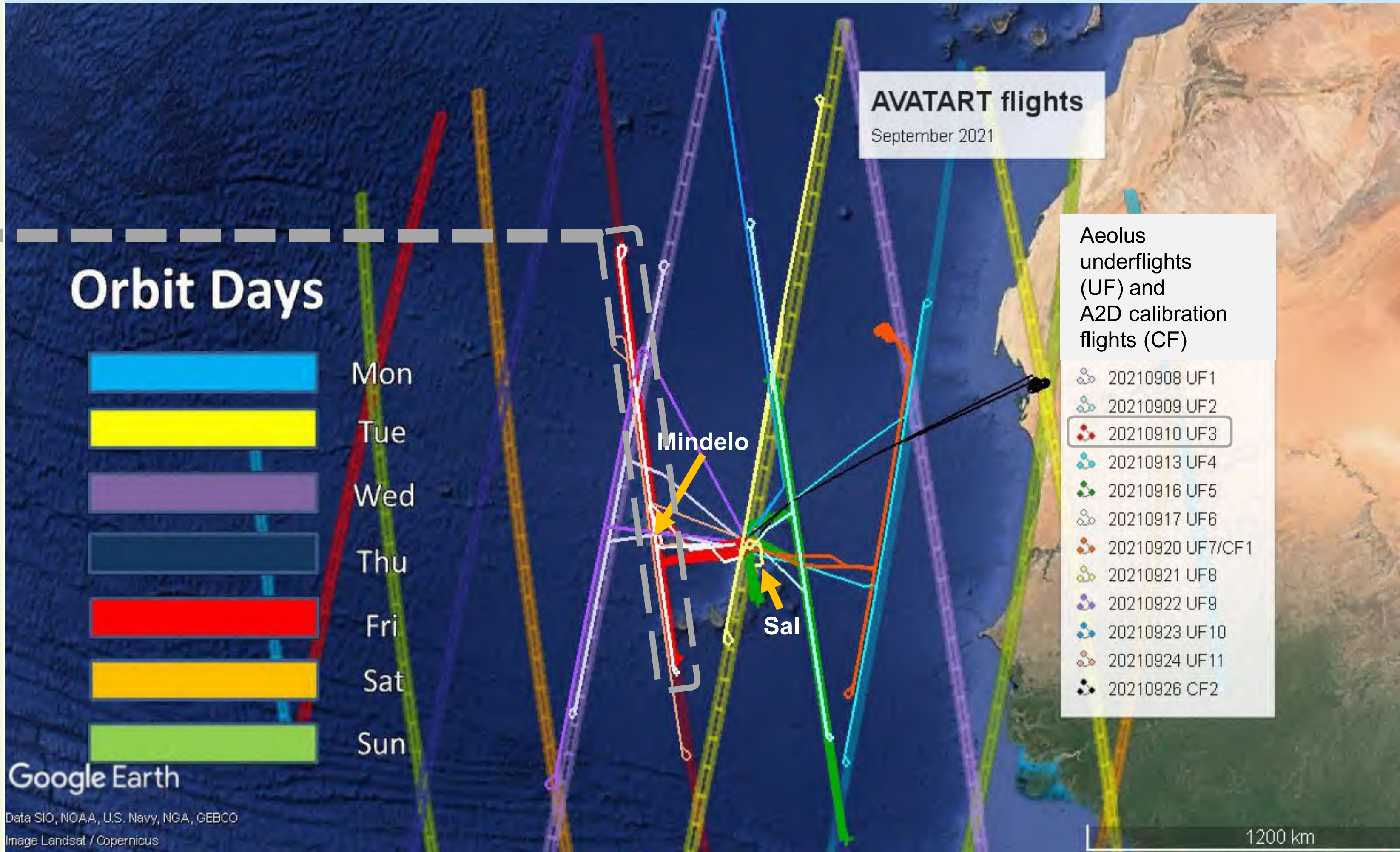
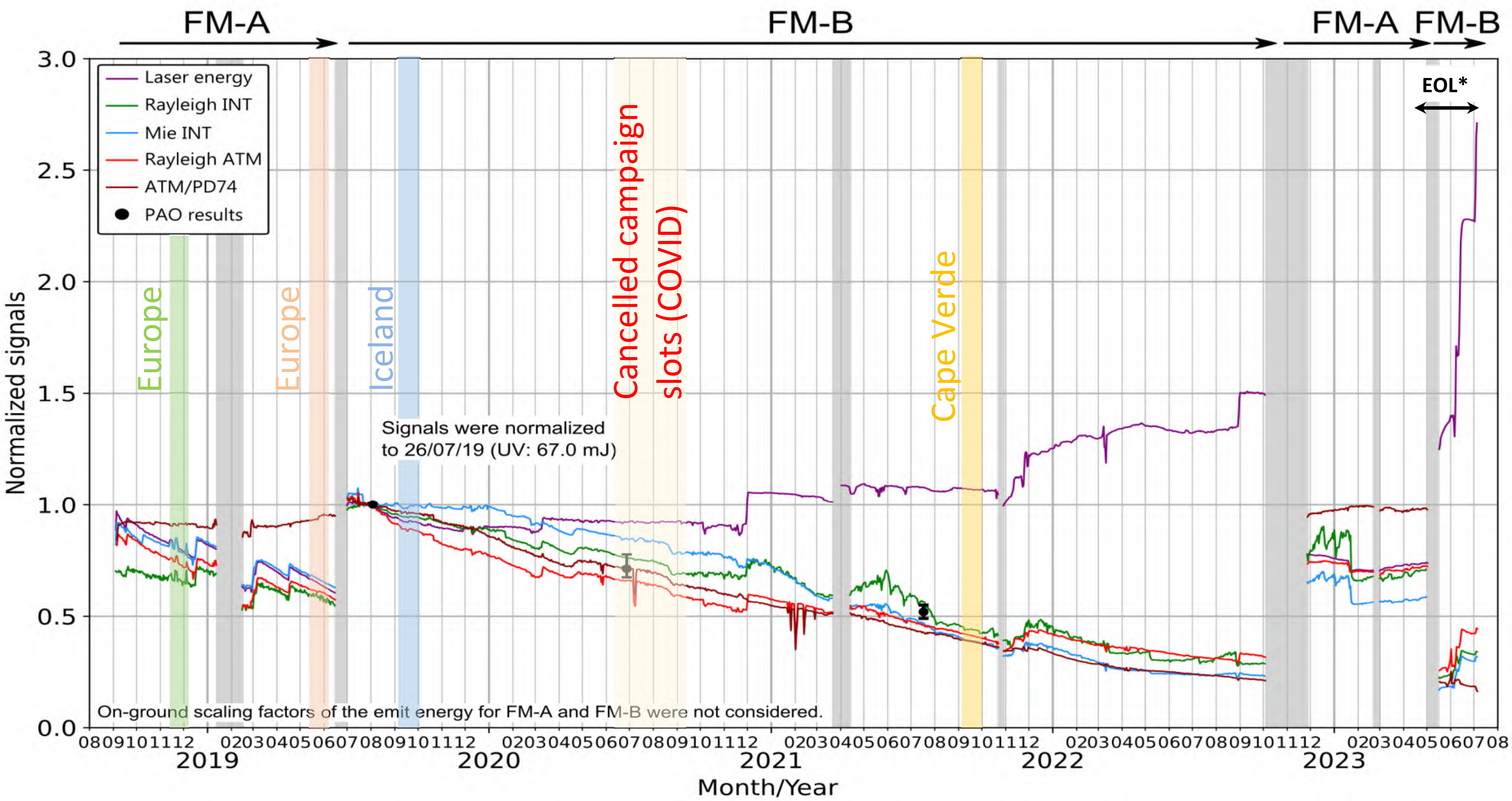


Aeolus Performance History and DLR Airborne Campaigns



* End-of-Life Activities phase

Dedicated Aeolus range bin settings (RBS) were applied for the campaign times and regions in Iceland and Cape Verde, to optimize the vertical overlap with the airborne lidar coverage

Aeolus Airborne Validation Campaigns Overview

4 airborne campaigns were performed (190 h for 52 flights* of which 31 were underflights providing a total of 26400 km along the Aeolus track) **under different conditions** (Aeolus performance, solar background, atmospheric dynamics, geographical regions)

➔ **High-resolution and high-quality airborne DWL data** intermediate perspective between ground- and Numerical Weather Prediction - based validation

Campaign time and location	Europe 2018	Europe 2019	Iceland 2019	Cape Verde 2021**
Aeolus RBS	Default (w/o) DEM	VAMP	AVATARI-2	Saturn-2
Active laser	FM-A	FM-A	FM-B	FM-B
Baseline operational	B02	B03	B06	B12
Reprocessed baselines	B14, (B16)	B14, (B16)	B10, B11, B16	B16
Compared baselines	**ongoing**	**ongoing**	(B06 vs.) **B11 vs. B16**	**B12 vs. B16**

* Incl. test, transfer and A2D calibration flights
** During Joint Aeolus Tropical Atlantic Campaign (JATAC/CPEX-AW, ESA/NASA)

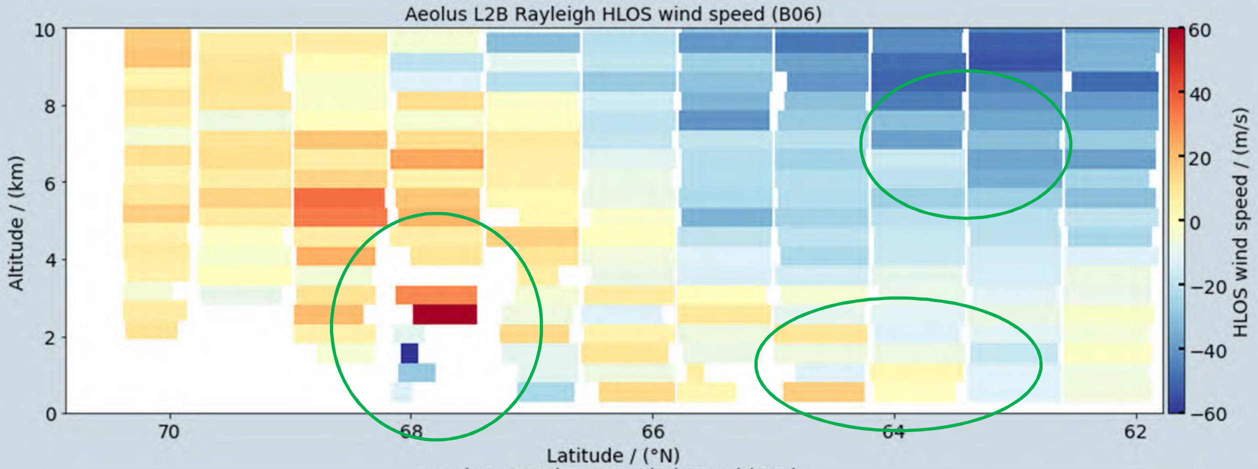
Aeolus Airborne Validation Example: Iceland 16/09/2019

- ➢ Heterodyne-Detection provides high coverage for the validation of both Aeolus Rayleigh and Mie channel results
- ➢ A2D Rayleigh and Mie channel are complementary
- ➢ Aeolus shows a lower Mie-cloudy winds coverage and Mie-contaminated Rayleigh-clear winds (higher noise/error)

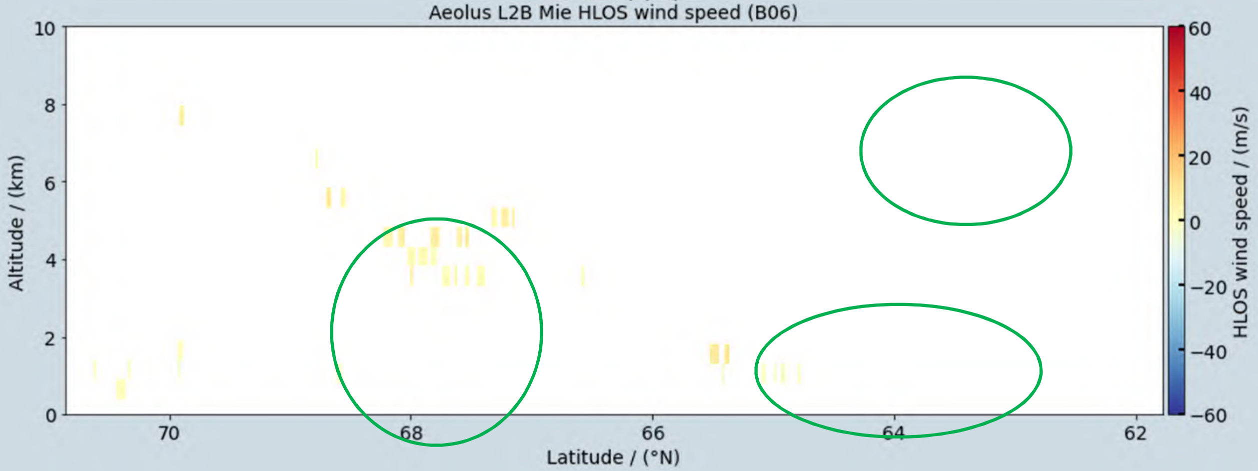
Aeolus horizontal line-of sight (HLOS) L2B winds

Baseline L2B06

Aeolus Rayleigh

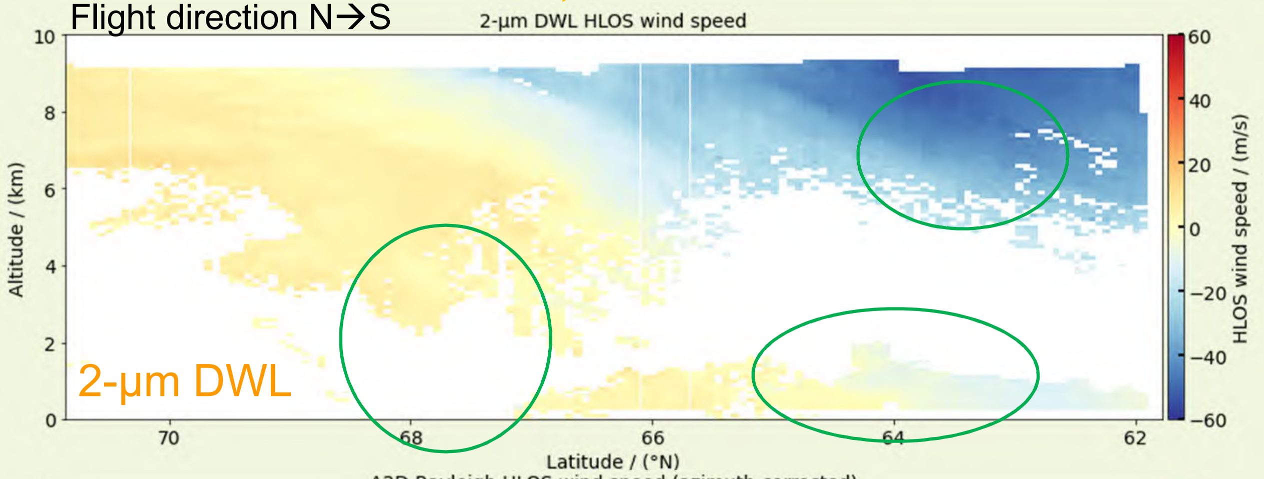


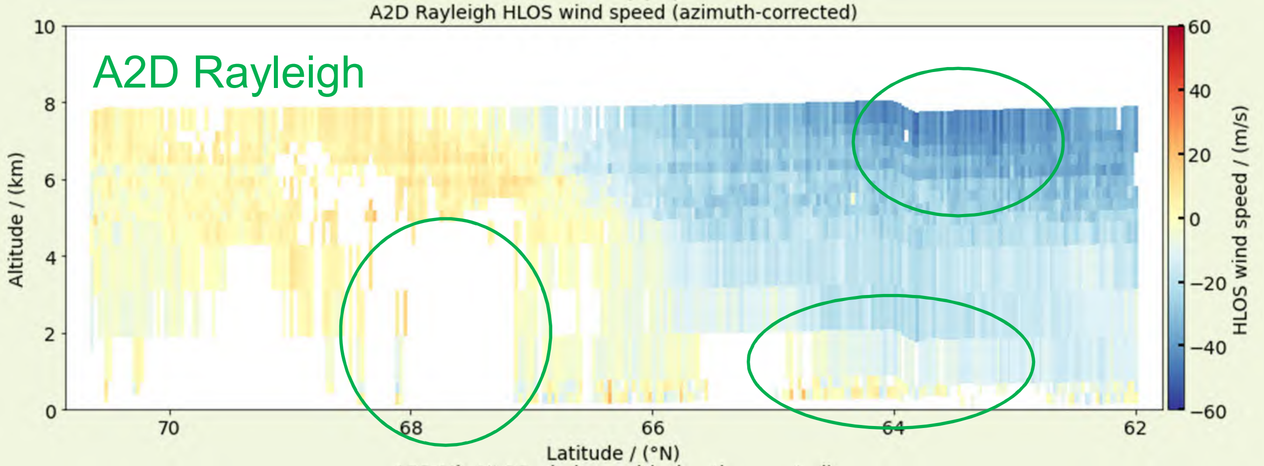
Aeolus Mie

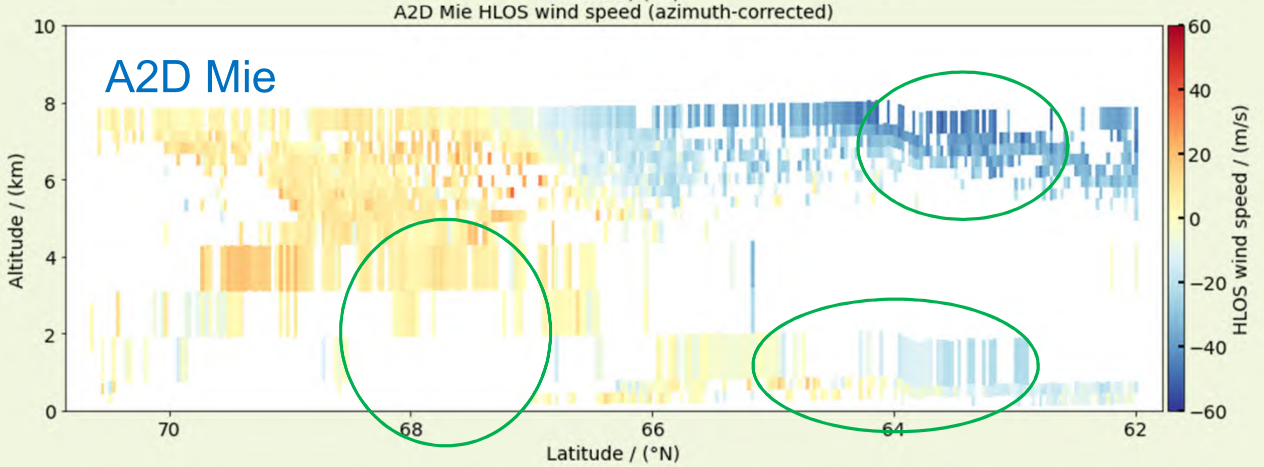


Airborne DWL winds on Aeolus HLOS

Flight direction N→S







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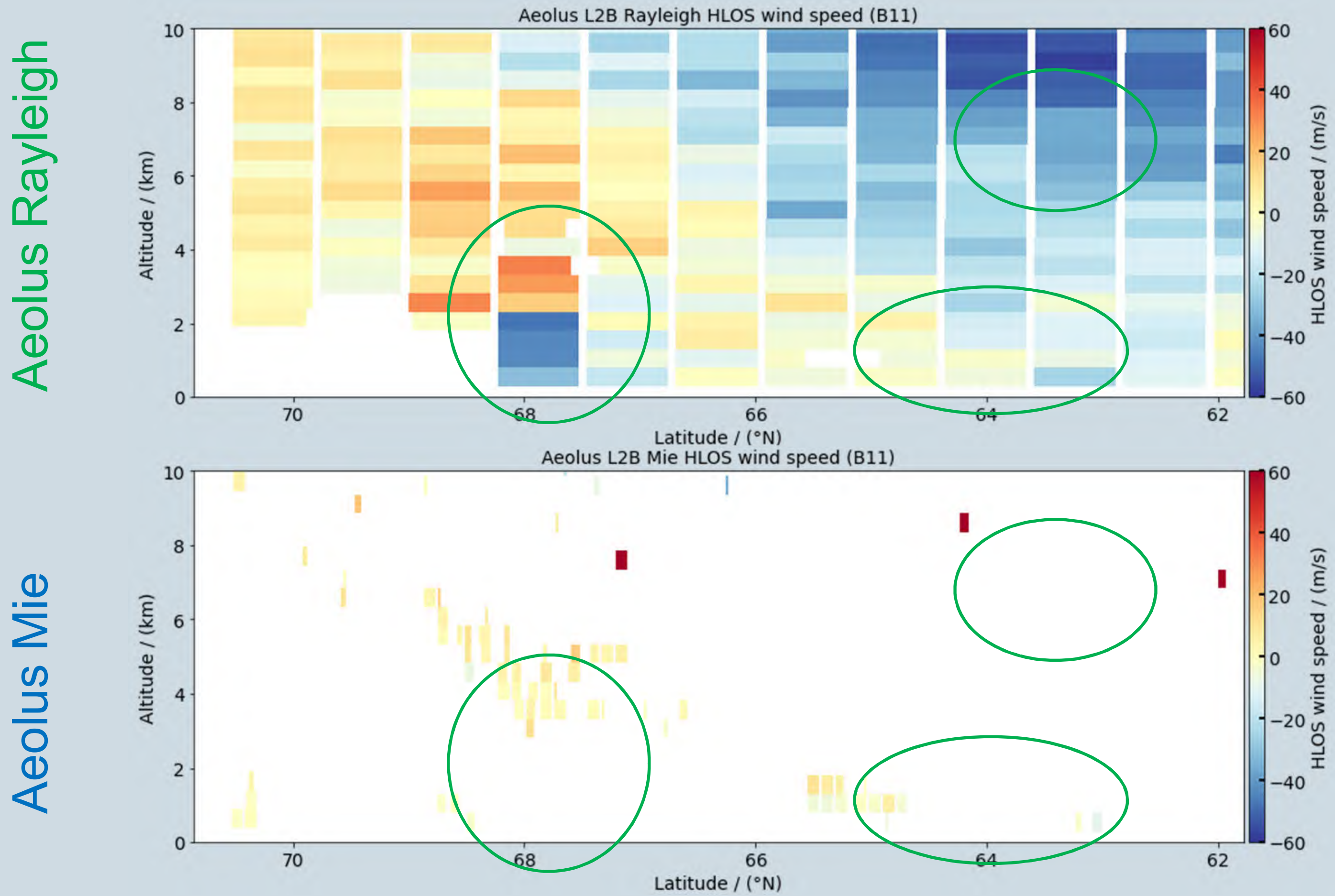
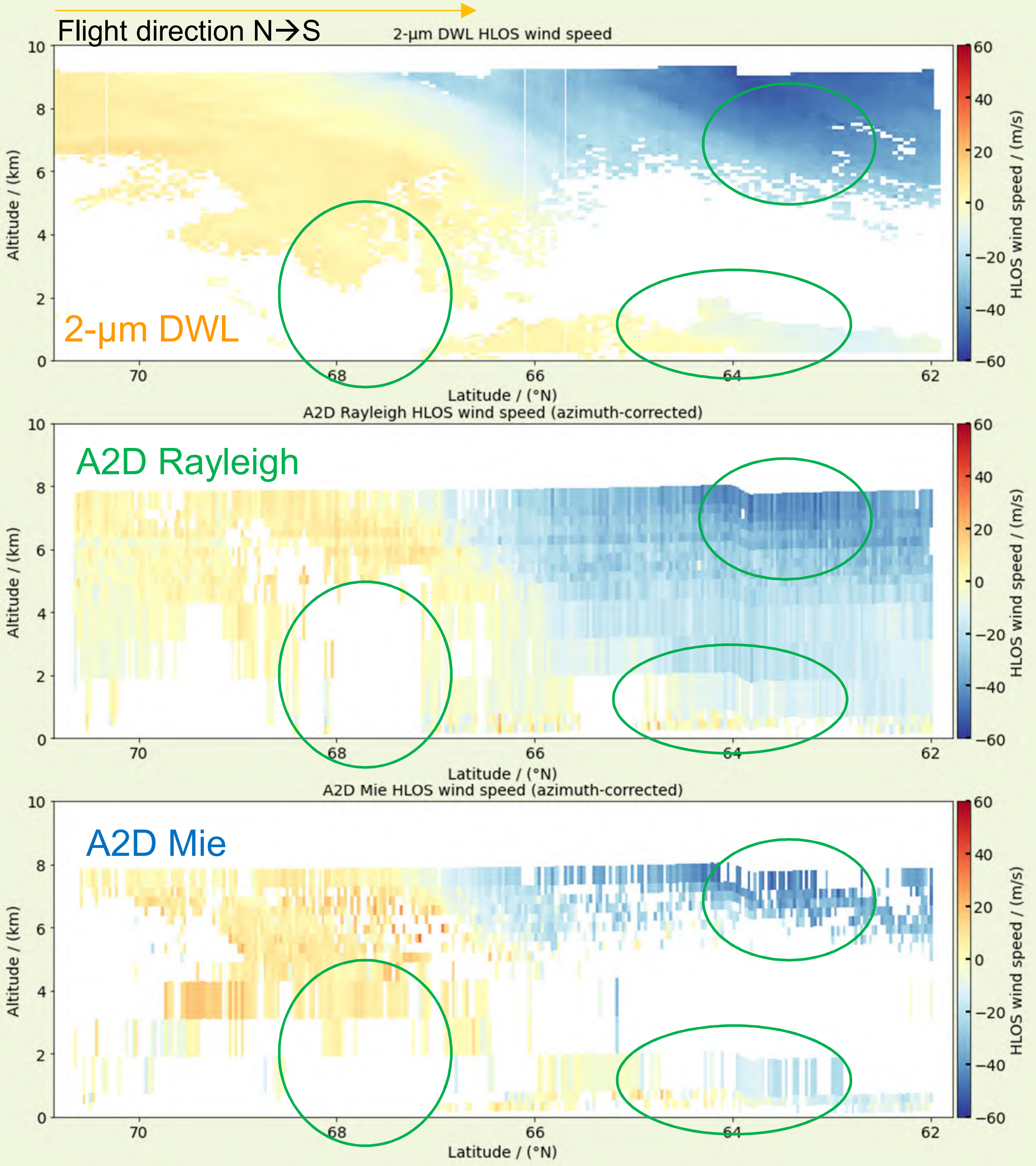
Aeolus horizontal line-of sight (HLOS) L2B winds

Baseline L2B11



Airborne DWL winds on Aeolus HLOS



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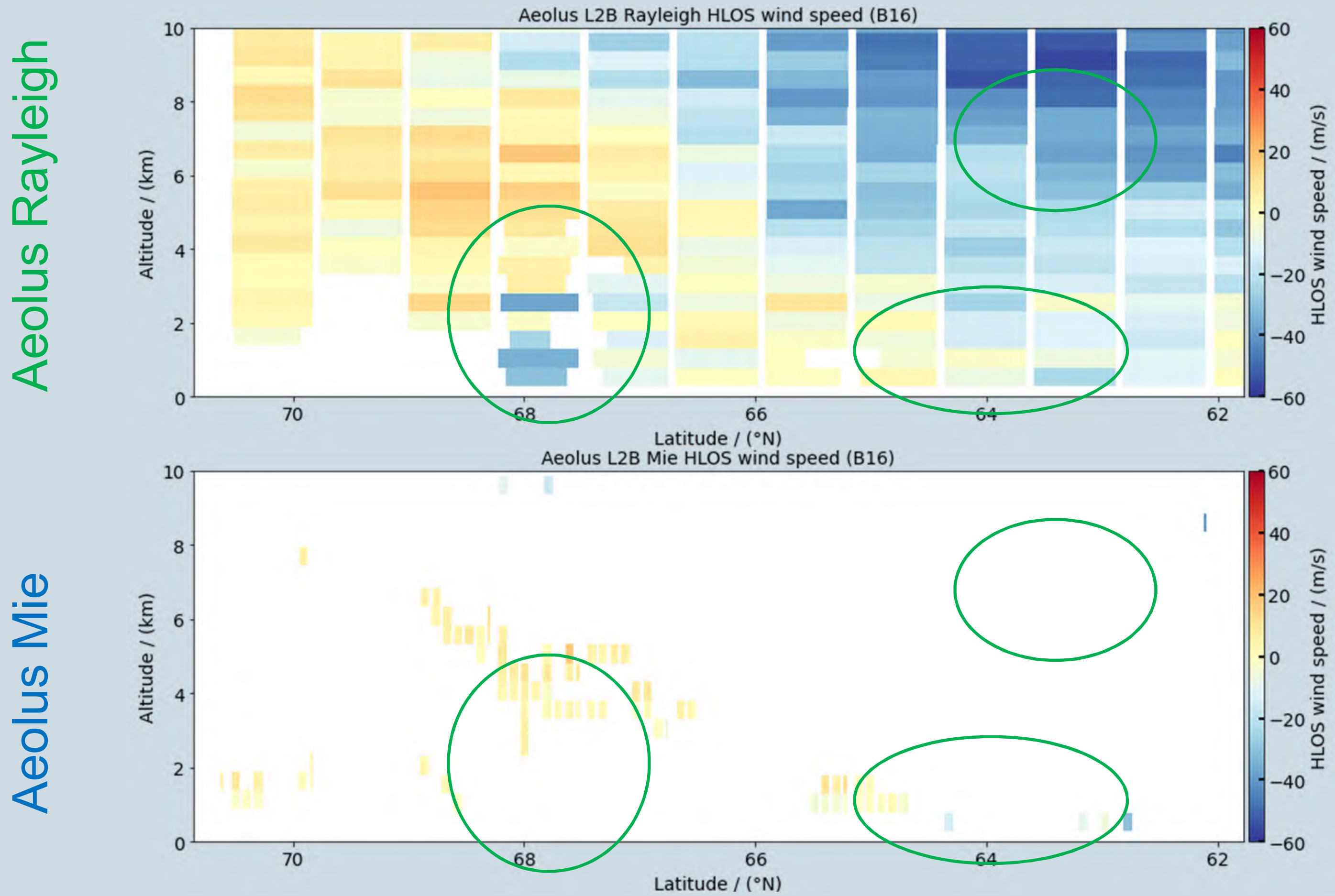
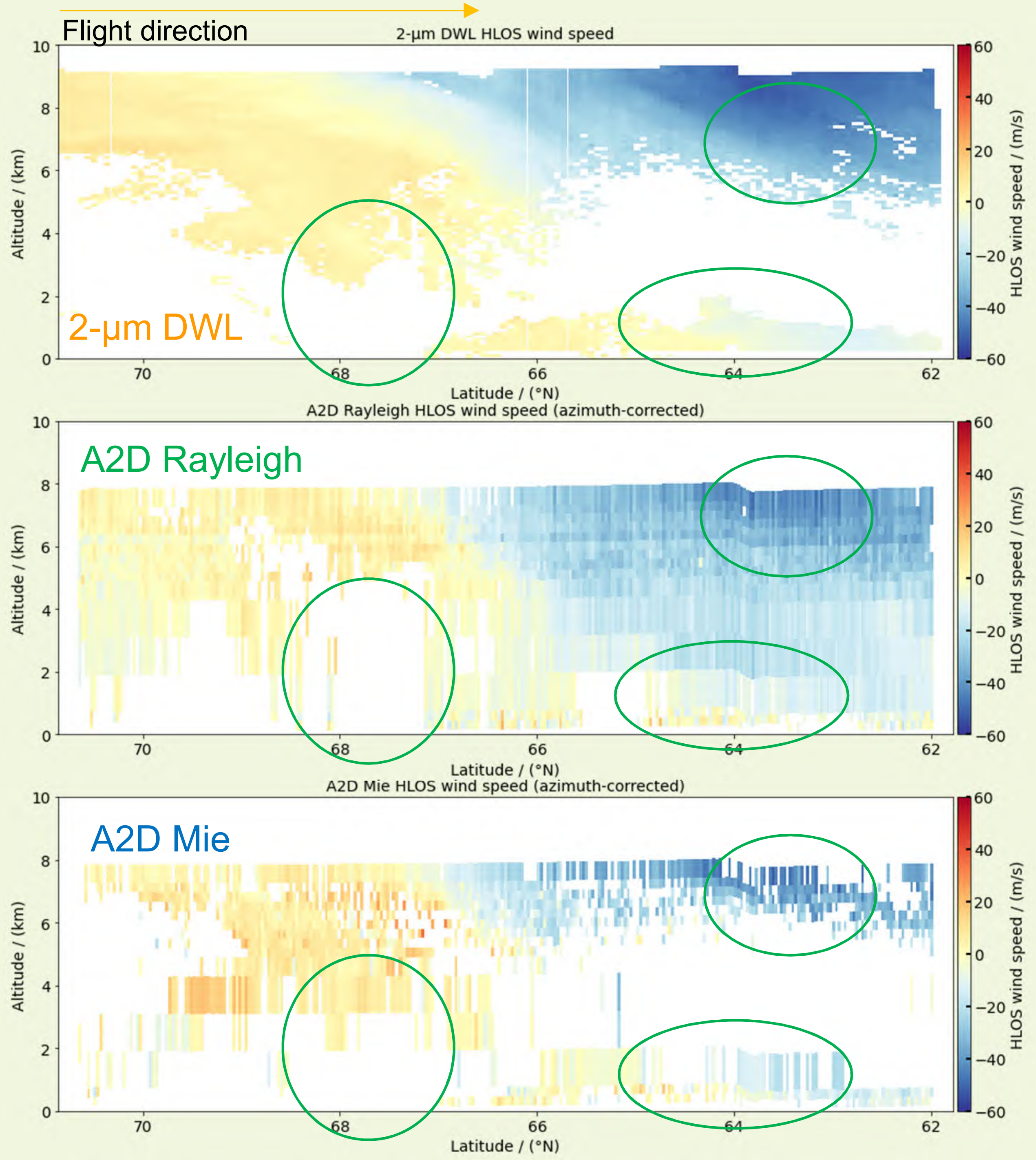
Aeolus horizontal line-of sight (HLOS) L2B winds

Baseline L2B16

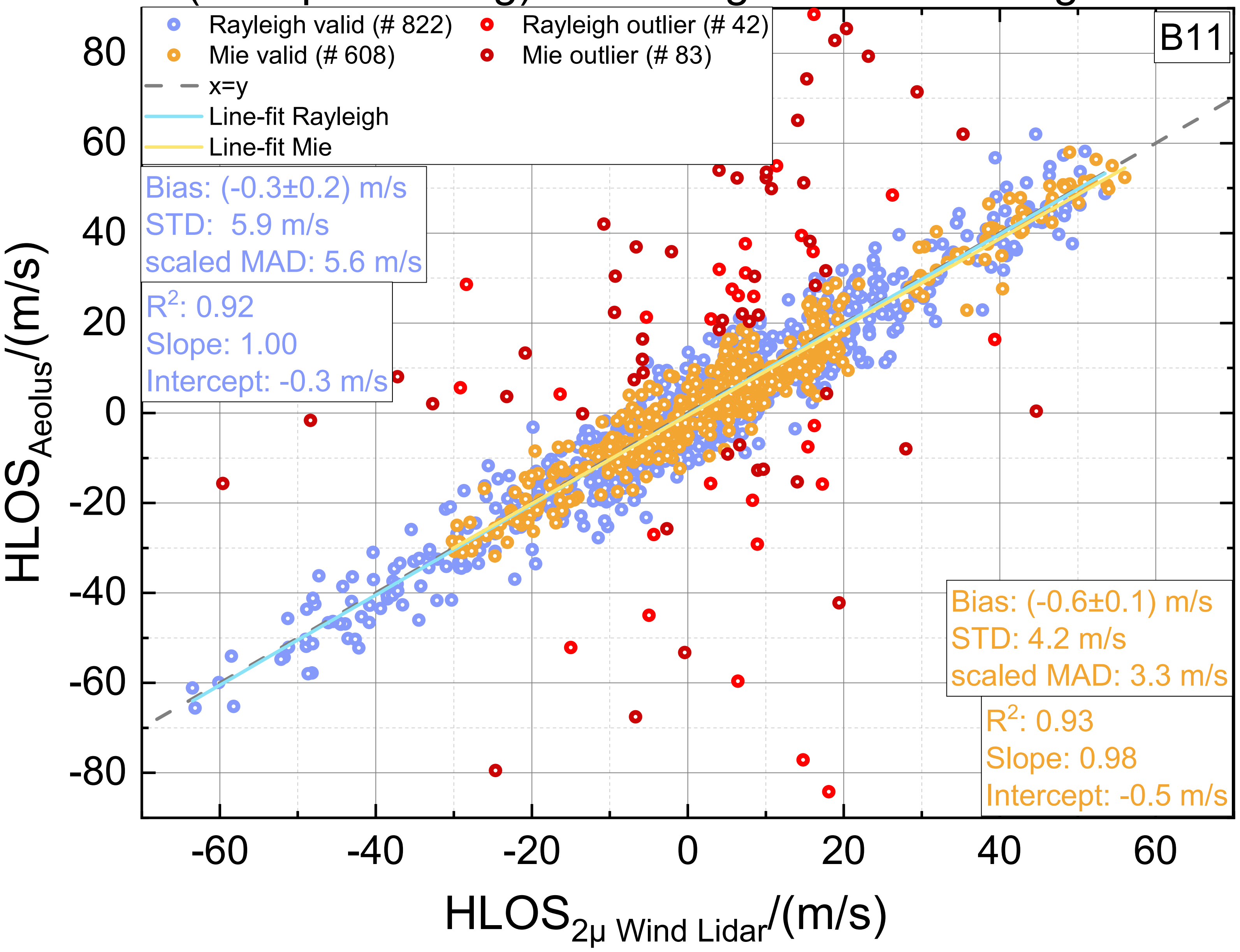


Airborne DWL winds on Aeolus HLOS



Statistical comparison B11 → B16 for the Iceland campaign, 2019

B11 (1st reprocessing) ascending and descending orbits



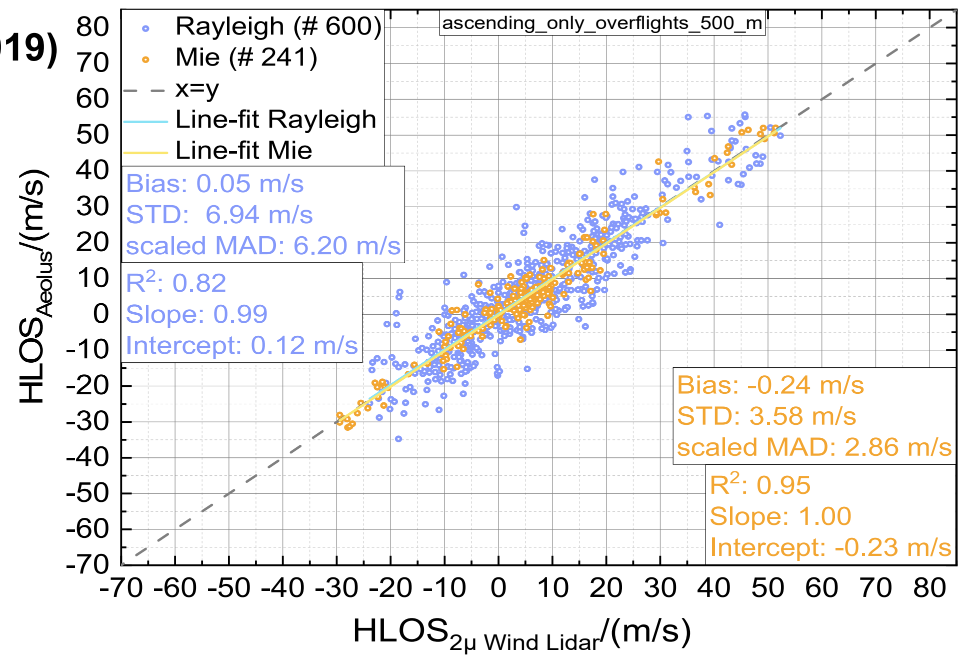
- 2-µm DWL 1-scan data, gridded to Aeolus L2B
- No EE threshold, only the median-modified Z-score is used as QC

B06

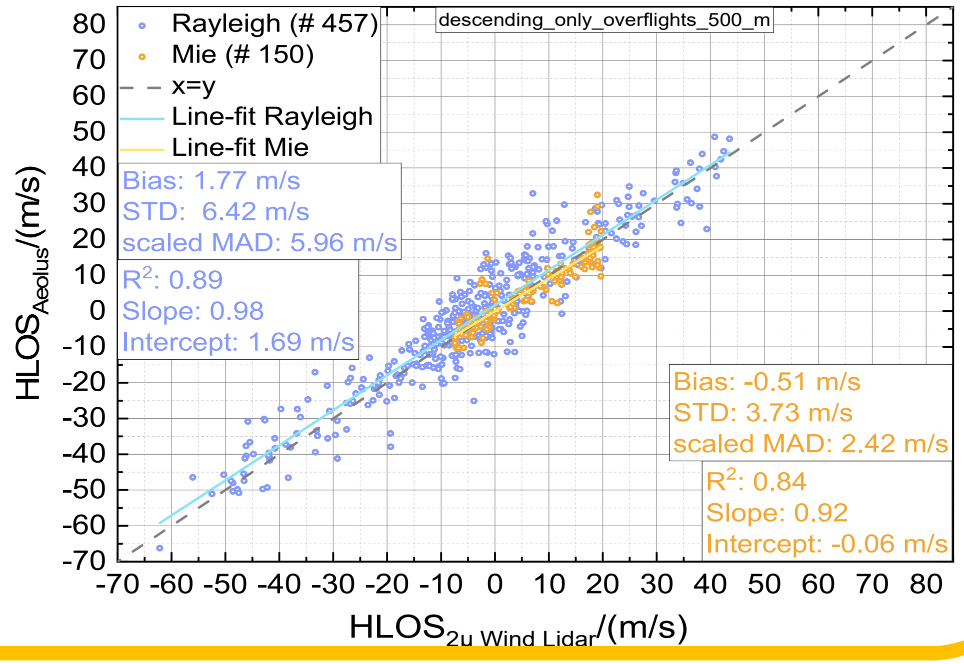
(NRT in 2019)

raw vertical resolution of 500 m;, 5-scan
estimated error threshold of 8 m/s (Rayleigh-clear) and 4 m/s (Mie-cloudy)

ascending-orbits

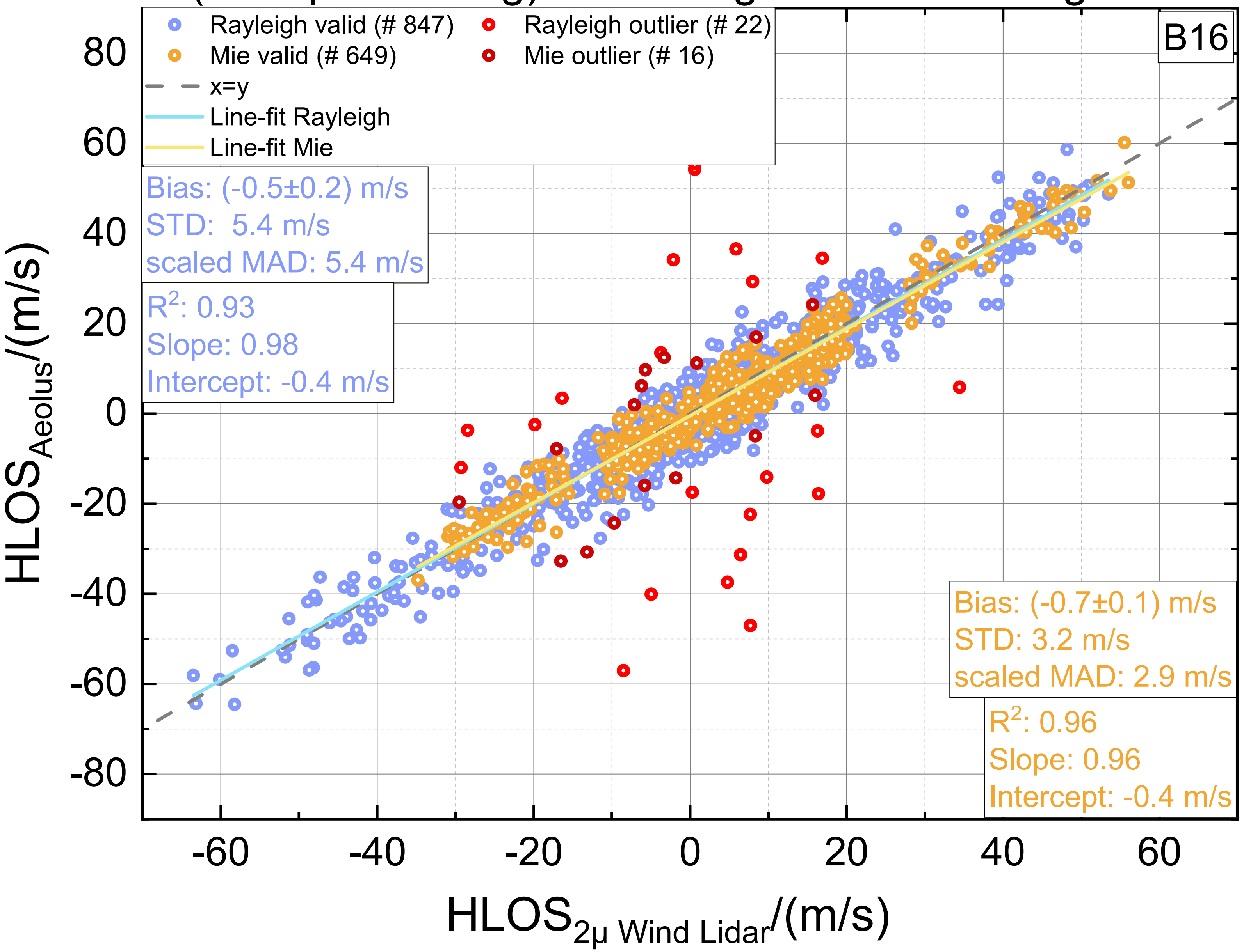


descending-orbits



Statistical comparison B11 → B16 for the Iceland campaign, 2019

B16 (3rd reprocessing) ascending and descending orbits



- 2-µm DWL 1-scan data, gridded to Aeolus L2B
- No EE threshold, only the median-modified Z-score is used as QC

A significant improvement in Aeolus HLOS wind quality is obvious from B11 to B16:

		# of valid data	# of outliers	Random error*
B11	Rayleigh	822	42	5.9 m/s
B11	Mie	608	83	4.2 m/s
B16	Rayleigh	847	22	5.4 m/s
B16	Mie	649	16	3.2 m/s
%	Rayleigh	+ 3%	- 48%	- 9%
%	Mie	+ 7%	- 81%	- 30%

* Random error given as scaled Median Absolute Deviation (MAD)

B16 main findings (including results not shown today):

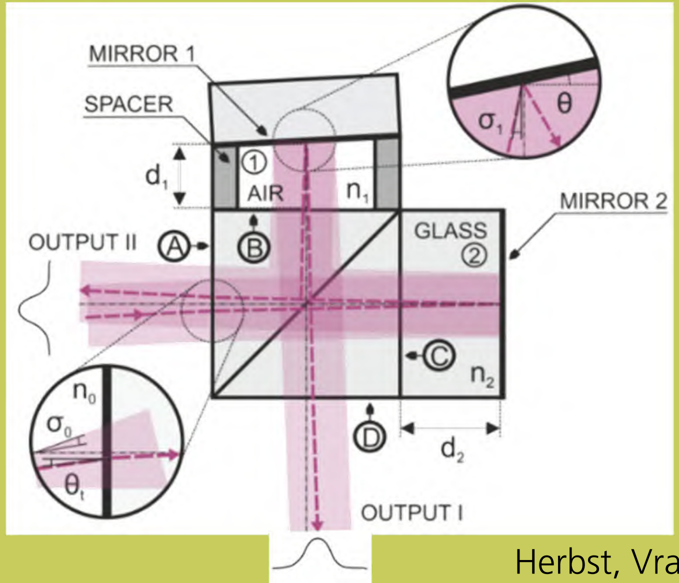
- Mie: Random error and estimated error products improved, less outliers with a more symmetrical distribution
- Biases are stable (within the uncertainties of the validation)
- The Rayleigh error estimate product better represents the wind error (is larger → necessary QC threshold adaptation) → AMT 2022 Lux et al., Witschas et al.
- A2D – Mie and Aeolus L1B data suggest potential to further increase the number of good quality Mie-cloudy winds in low-SNR conditions

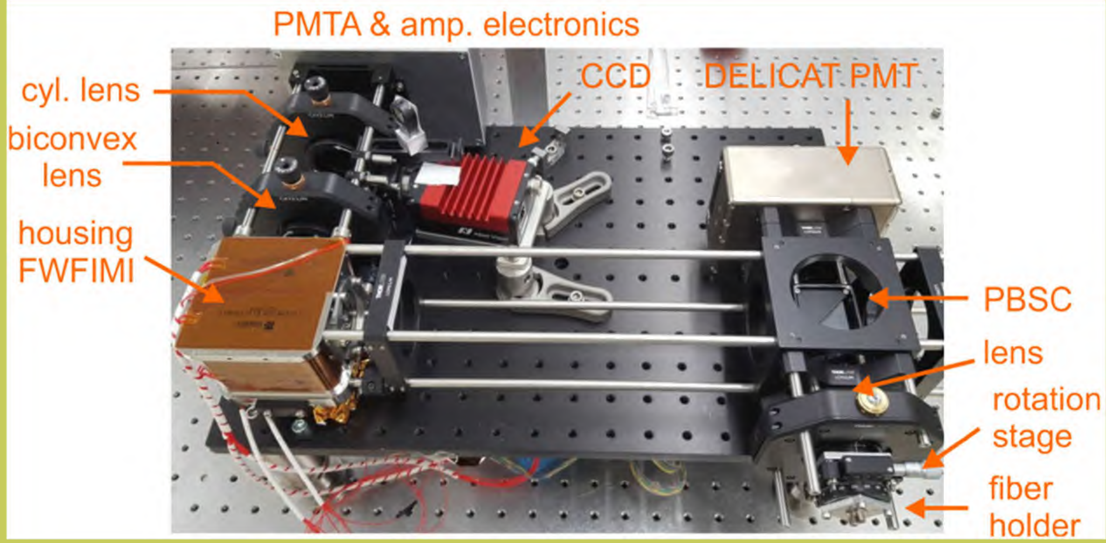
The Close and (Potential) Long-Term Future

- A2D results will continue to support the mission processor development and re-processing results verification
- A2D 2nd generation on Falcon successor and newly developed laser 60 mJ, 100 Hz incl. adapted detection electronics (double horizontal resolution)
  ➔ **Investigations for Aeolus-2:** Cross-polar channel, new detector (and Rayleigh spectrometer)?

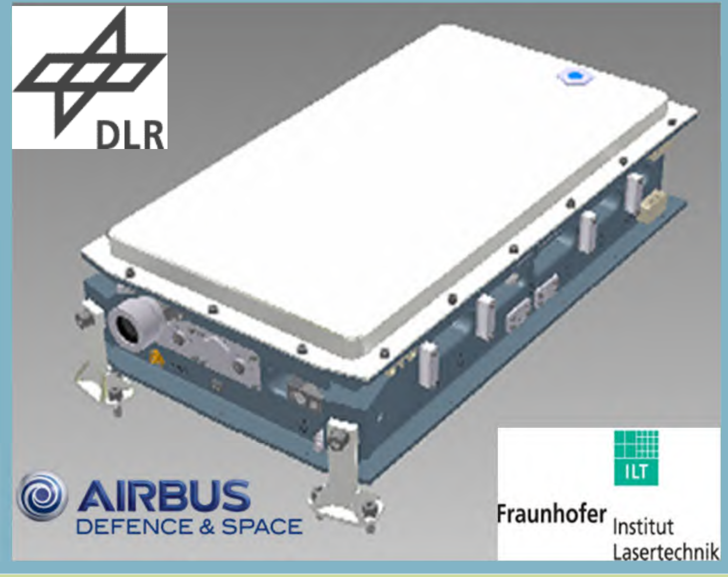
- New heterodyne-detection reference DWL @ 1.6 µm with scanner (1.7 mJ, 750 Hz) and an expected improved coverage and horizontal resolution fielded for NAWDIC in Jan. 2026

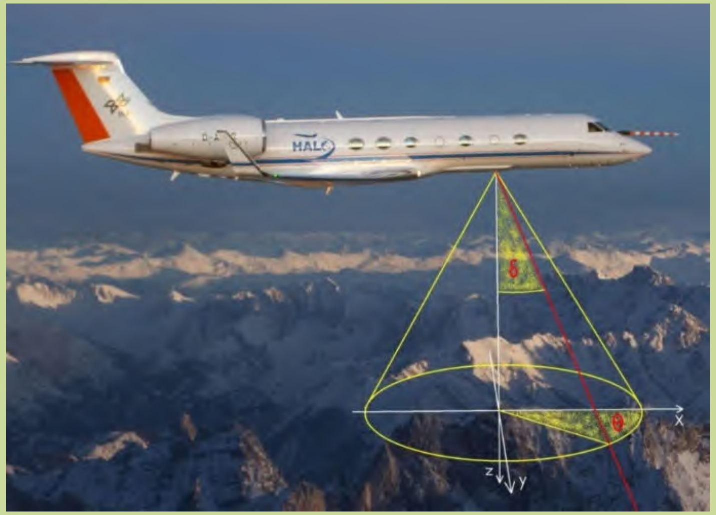
- In-house cooperation on the development of a 355 nm direct detection DWL for aviation (gust detection), based on a field-widened Michelson spectrometer with fringe-imaging





Herbst, Vrancken 2016, Appl. Opt.



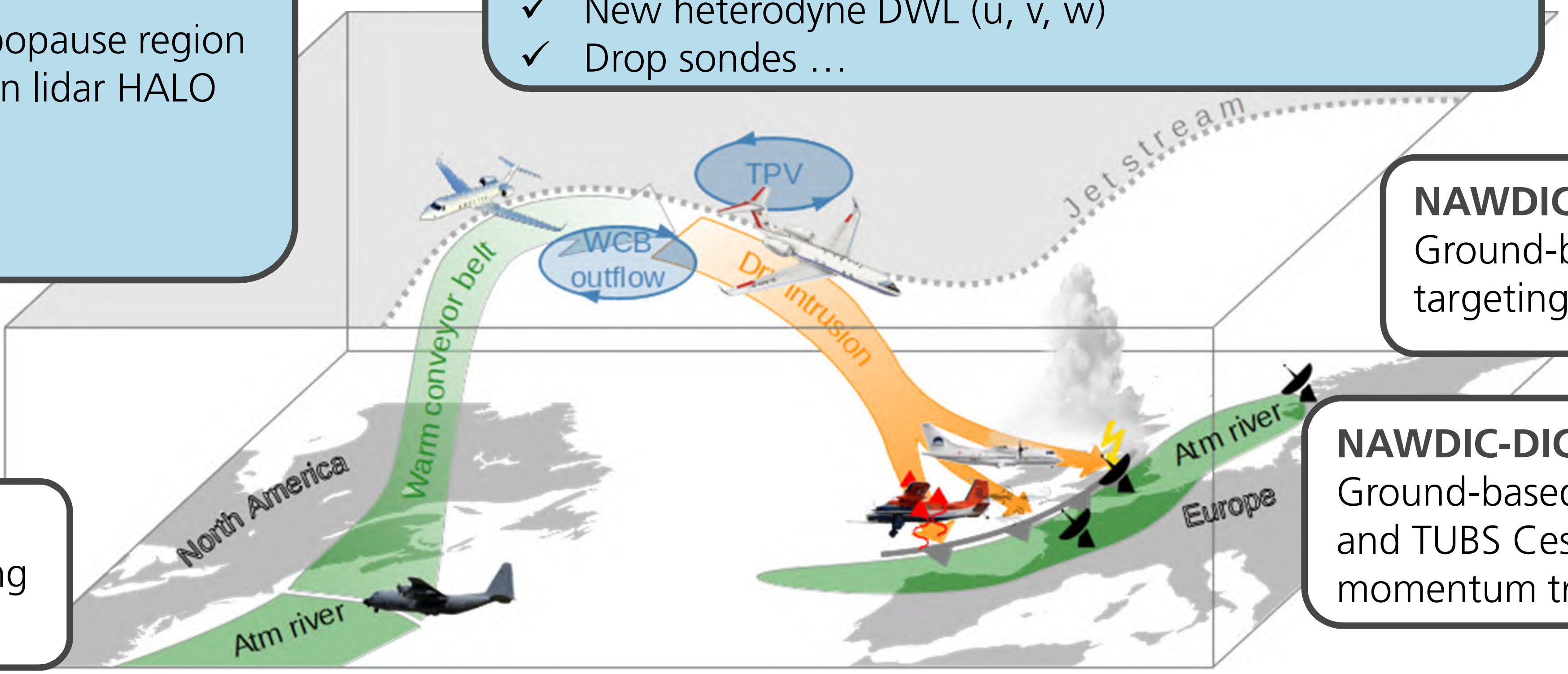


North Atlantic Waveguide, Dry intrusion, and downstream Impact Campaign

➔International effort to advance the understanding of PBL interactions and tropopause dynamics associated with the triggering of high-impact weather

NAWDIC-HALO (DE):
HALO aircraft targeting DIs
- ✓ Differential absorption lidar WALES (H_2O, O_3, aerosol)
- ✓ New heterodyne DWL (u, v, w)
- ✓ Drop sondes …

NURTURE (US):
NASA G-III targeting tropopause region
- ✓ Differential absorption lidar HALO (H_2O, O_3, aerosol)
- ✓ Cloud radar (Ka, W)
- ✓ Drop sondes …



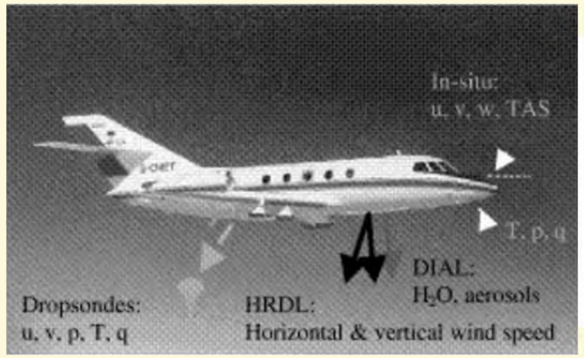
NAWDIC-KITcube (DE):
Ground-based measurements targeting DI-PBL interactions

NAWDIC-DICHOTOMI (FR/DE):
Ground-based measurements, ATR42 and TUBS Cessna targeting downward momentum transport

AR Recon (US):
Mid-range aircraft targeting atmospheric rivers

Historic context of water vapor flux measurements:

DWL & H_2O-DIAL on DLR Falcon in 2002 (IHOP) - US, 2007 & 2008 with focus on pre-convective environment over Europe (COPS) and Arctic Ocean (IPY-THORPEX)



AIRBORNE DIAL MEASUREMENTS OF WATER VAPOUR AND VERTICAL MOISTURE FLUX DURING IHOP 2002

Gerhard Ehret[1], Christoph Kiemle[1], Andreas Fix[1], Harald Flentje[1], Gorazd Poberaj[1], Martin Wirth[1], R. Michael Hardesty[2], W. Alan Brewer[2], Scott P. Sandberg[2], Brandy McCarty[2]

Summary

After a comprehensive pre-launch program deploying the A2D and 2-µm DWLs, four airborne campaigns were performed for the Aeolus wind validation under different conditions (Aeolus performance, geographical region and atmospheric dynamics)*

***Activities co-funded by DLR and ESA**

➔ The heterodyne and direct detection DWLs' synergistic and partly complementary data coverage allowed us to validate the Aeolus wind data products and to derive suggestions for further Aeolus processor developments

➔ Characterization of wind bias, random and estimated error for operational and reprocessing baselines up to B16 show improved Aeolus data quality (random error Mie-cloudy 3.2 m/s, Rayleigh-clear 5.4 m/s for the FM-B 2019 best performance case)

➔ The four airborne campaigns **covering the whole mission phase** and a **wide windspeed range** were crucial for the model-independent validation of Aeolus winds

Courtesy Gilles

Outlook

- DLR airborne campaigns datasets continue to **support and validate on-going Aeolus processor developments for wind and potentially aerosol products.**
- **The Aeolus preparation and validation success** featuring the A2D as a suborbital trailblazer and companion for the mission, paired with a heterodyne reference DWL is highly **recommended** by DLR **for being applied to the coming Aeolus generation**
- The campaign activities align with the vision of developing complementary and synergistic products from a mixed-technology DWL and water vapor DIAL **satellite constellation during the Aeolus-2 phase** (mid-2030s and beyond)

Workshop on Space-based Measurements of 3-Dimensional Winds

THANK YOU!

19 to 20 February 2025, Earth System Science Interdisciplinary Center (ESSIC), College Park, MD