DLR’S AIRBORNE SUPPORT OF ESA’S AEOLUS MISSION
FROM PRE-LAUNCH CAMPAIGNS TO MISSION PERFORMANCE VALIDATION

Benjamin Witschas, Christian Lemmerz, Oliver Lux, Stephan Rahm, Uwe Marksteiner, Alexander Geiß, Fabian Weiler and Oliver Reitebuch

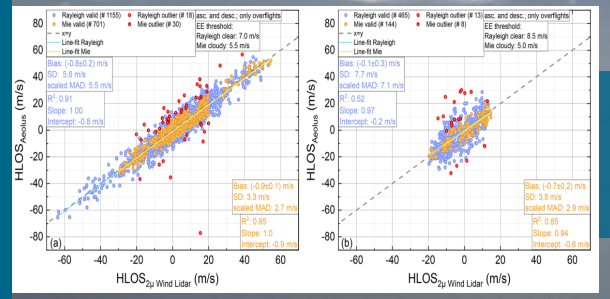
Optica Laser Congress and Exhibition, 11 – 15 December 2022, Barcelona, Spain

DLR

OUTLINE

ESA‘s Aeolus mission

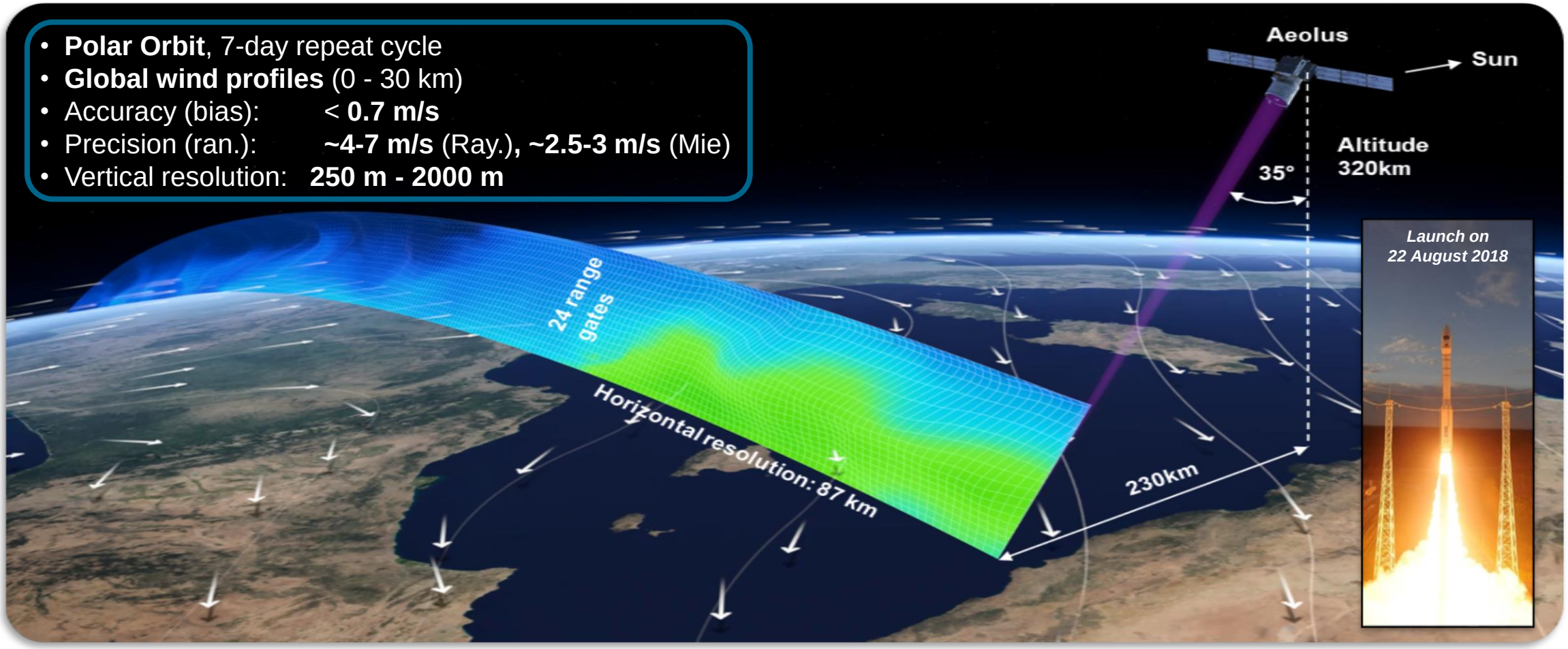
DLR‘s airborne Aeolus CalVal payload



Results from pre- and post launch campaigns

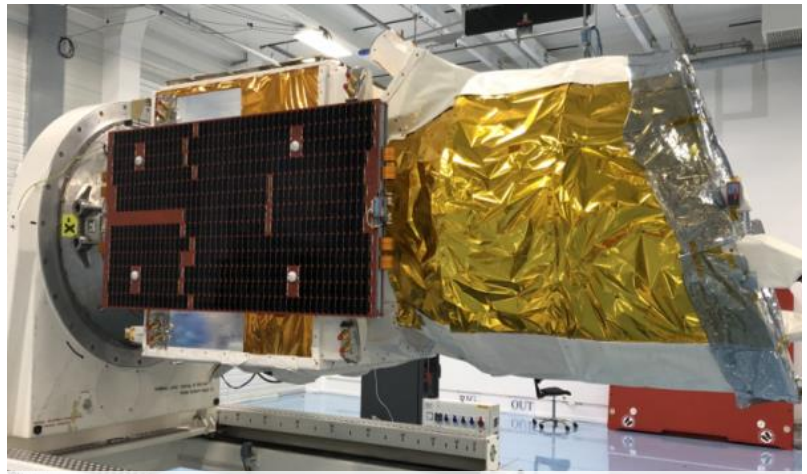
ESA‘s Aeolus Mission
ALADIN – the first spaceborne wind lidar

- Before the launch of Aeolus, the knowledge of the atmospheric wind field was insufficient → precise global wind profile measurements were fundamental to improving numerical weather prediction

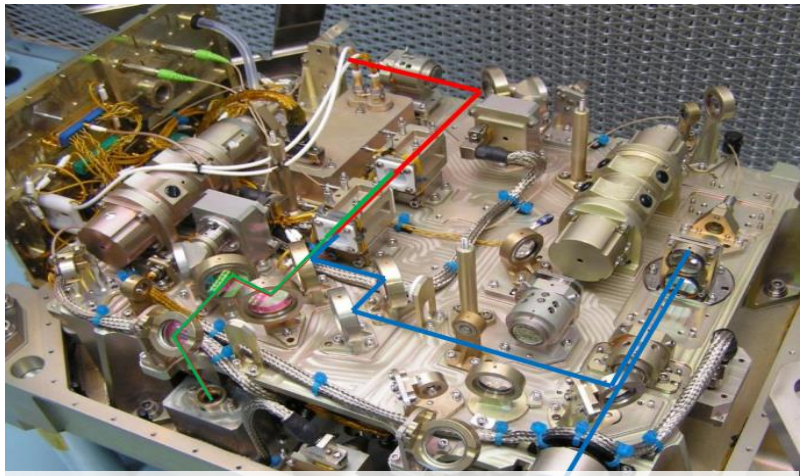


References: ESA, 1999 - The four candidate earth explorer core missions, Reitebuch et al., J-TECH, 2009, Fig. Credits ESA

ESA‘s Aeolus Mission
A technological challenge



Aeolus satellite



ALADIN laser transmitter

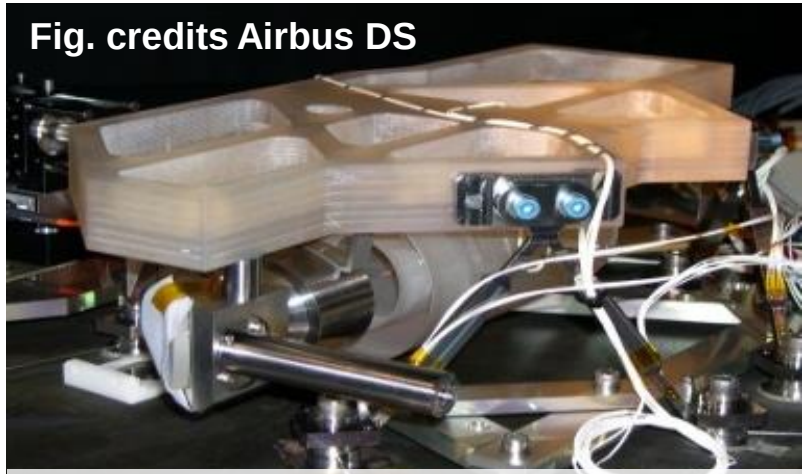
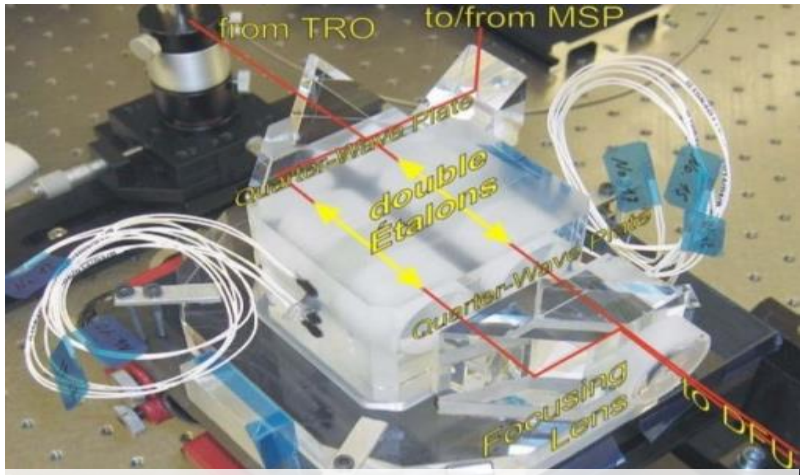


Fig. credits Airbus DS

Mie spectrometer



Rayleigh spectrometer

- **First European lidar mission** after 20 years of challenging development
- **First spaceborne wind lidar**
- **First spaceborne high-power UV laser** with stringent requirements on frequency stability

All mission goals reached:

- Technology successfully demonstrated
- Exceeded mission time **(> 4 years instead of 3 years)**
- Demonstrated **significant positive impact for numerical weather prediction** by several weather centers (e.g. ECMWF, Meteo France, DWD, etc.)

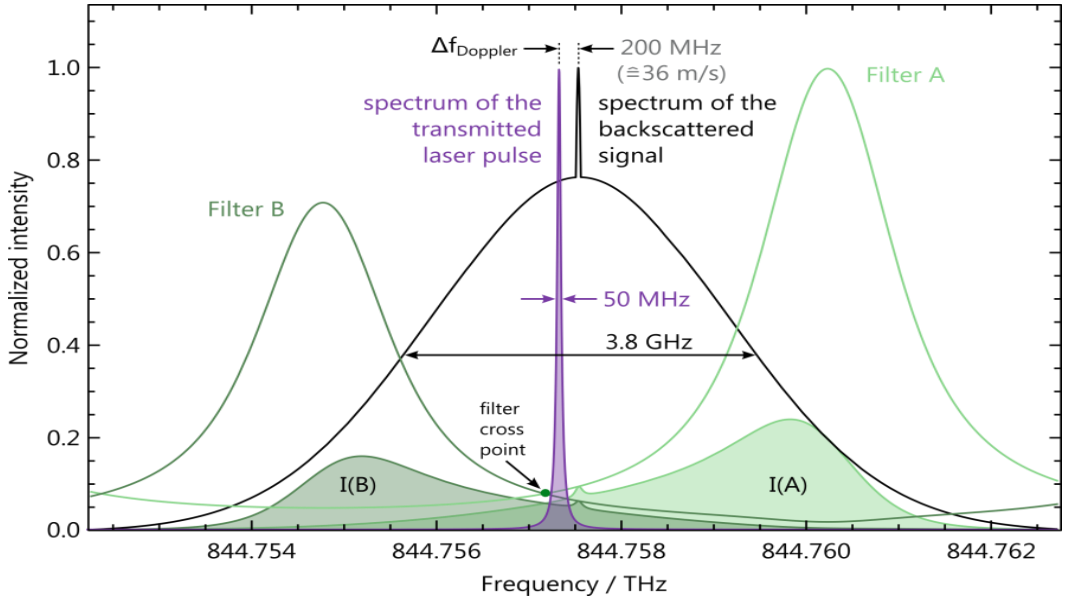
References: ESA, 1999 - The four candidate earth explorer core missions, Reitebuch et al., J-TECH, 2009, Reitebuch, Springer, 2012, Reitebuch/Hardesty, Springer, 2022; Lux et al., 2022, Opt. Lett

ESA‘s Aeolus Mission
Aeolus measurement principle

Winds measured from **molecular backscattered light**

(Rayleigh-clear winds)

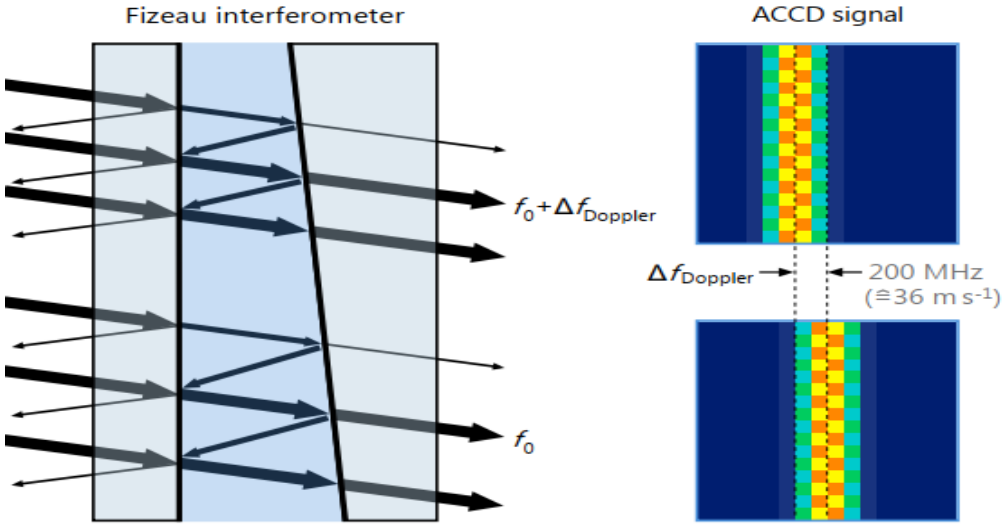
based on the so-called double-edge technique.



Winds measured from light **backscattered on aerosols and clouds**

(Mie-cloudy winds)

based on the so-called fringe imaging technique.



Doppler-Equation: $\Delta f = 2\, f_0\, \frac{v_{LOS}}{c}$

relative Doppler shift $\Delta f/f_0 \approx 10^{-8}$ for 1 m/s

1 m/s (LOS) ⇔ 5.64 MHz ⇔ 2.37 fm

size H-atom 50 pm, H-nucleus 1.2 fm

Simple measurement principle but complex technology and high accuracy required

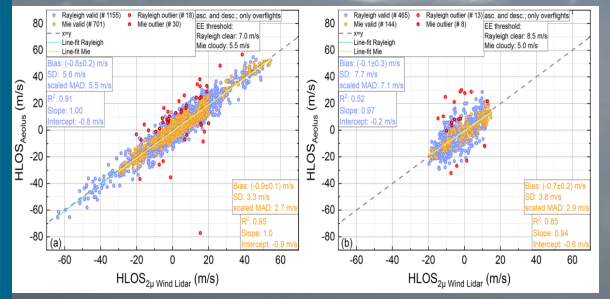
→ Need for validation of the measurement principle and technology under real atmospheric conditions

References: Lux et al., AMT, 2018

OUTLINE

ESA‘s Aeolus mission

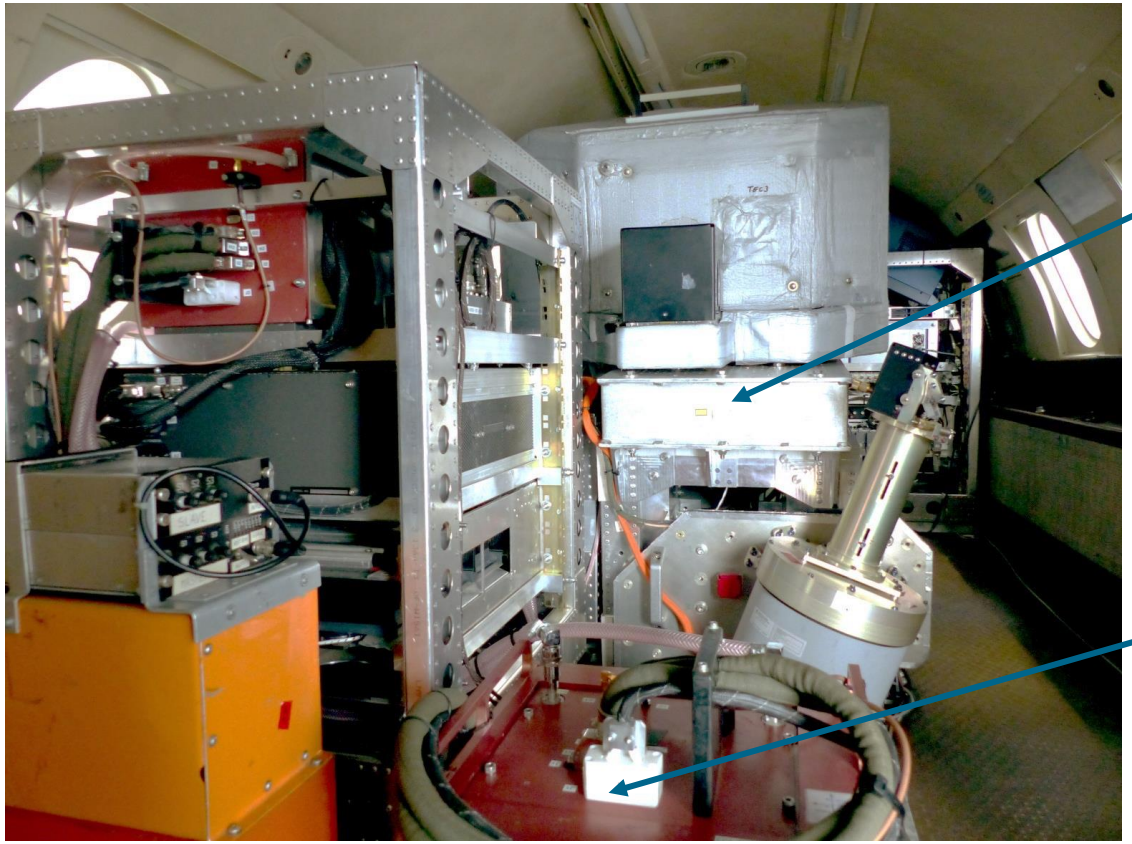
DLR‘s airborne Aeolus CalVal payload



Results from pre- and post launch campaigns

ESA‘s Aeolus Mission
The airborne Aeolus Cal/Val payload at DLR

To demonstrate the Aeolus measurement principle, optimize the Aeolus calibration strategy as well as to support the Aeolus retrieval developments, **DLR developed an airborne Aeolus calibration and validation payload that has been operated since 2005**.



The ALADIN airborne demonstrator (A2D):

Prototype of the ALADIN instrument with a representative design and measurement principle.

→ Used to validate the Aeolus **measurement principle**, **calibration** procedures, and **retrieval** algorithms.

The 2-µm Reference Lidar:

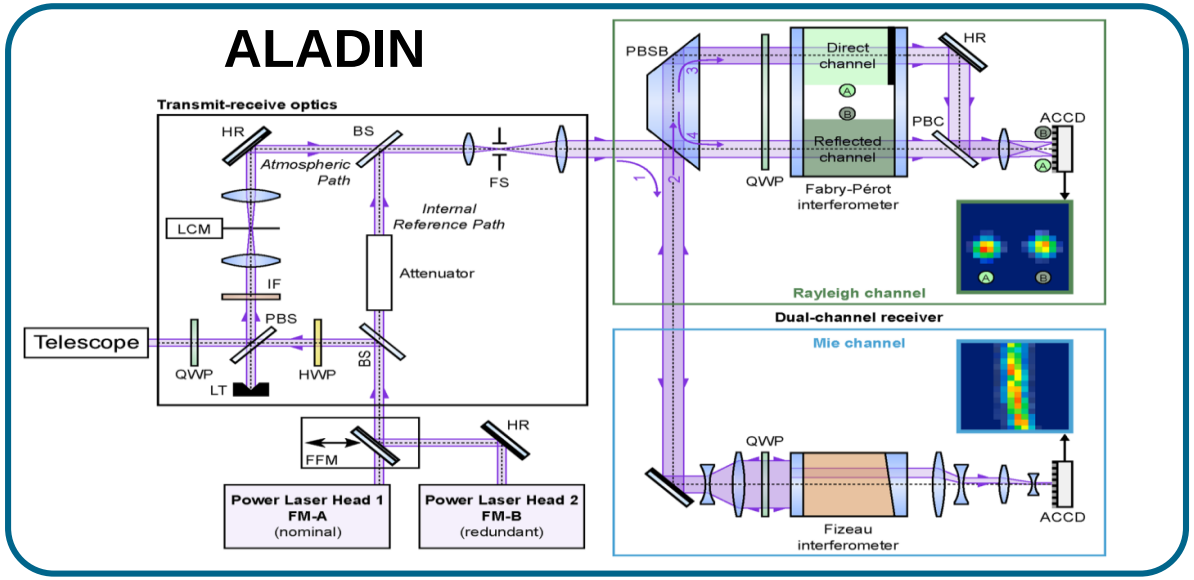
A highly-accurate, heterodyne-detection wind lidar with a high sensitivity to particulate returns operated as a reference system.

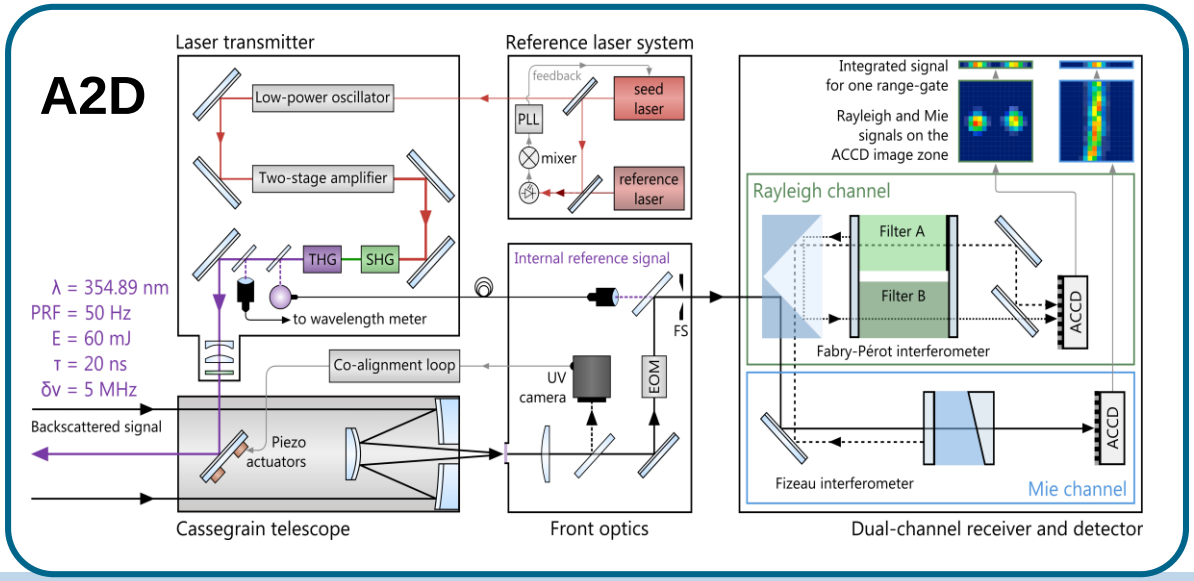
→ Used for **validation and error assessment**

References: Reitebuch et al., (2009), J-TECH; Lux et al. (2018), AMT; Marksteiner et al. (2018), Rem. Sens.; Witschas et al (2017), J-TECH; Witschas et al. (2022), AMT

ESA‘s Aeolus Mission

ALADIN on Aeolus and the Airborne Demonstrator (A2D)

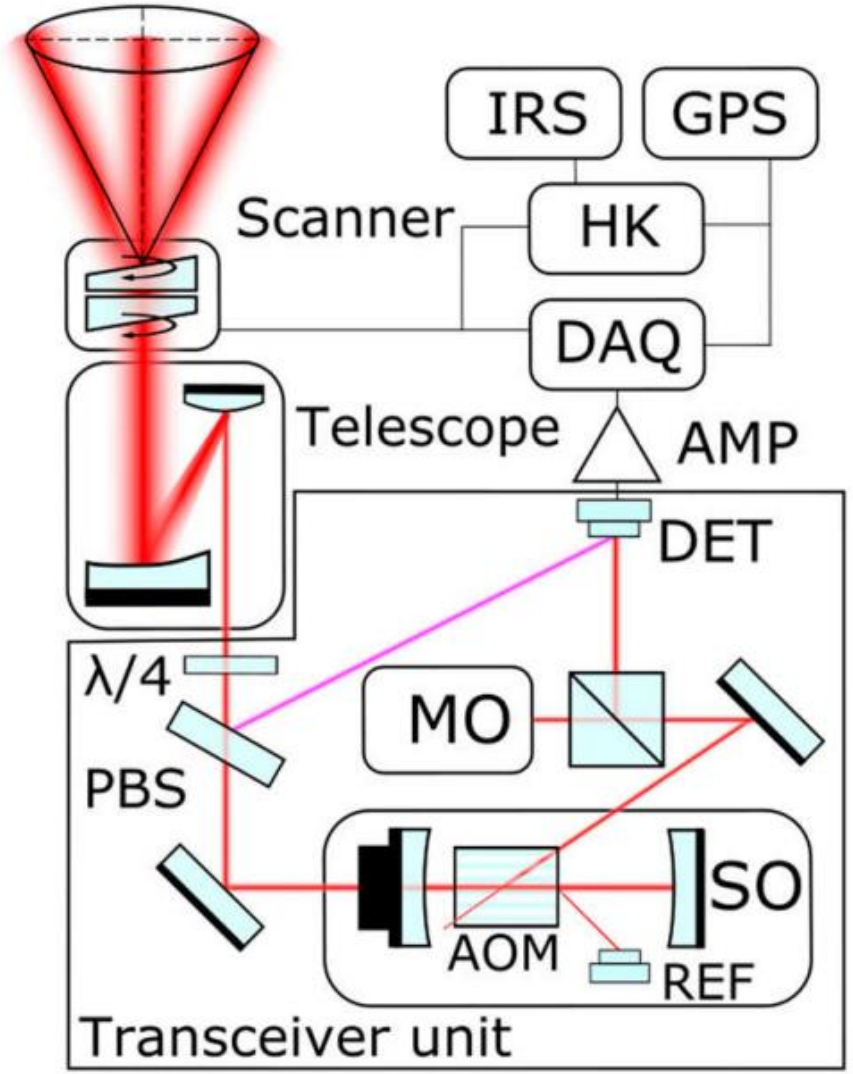




Parameter	ALADIN	A2D (Demonstrator)
Laser wavelength	354.8 nm	354.9 nm
Repetition rate	50.5 Hz	50 Hz
Pulse energy	53…101 mJ	60 mJ
Linewidth	30 MHz (FWHM)	50 MHz (FWHM)
Telescope diameter	1.5 m	0.2 m
LOS slant angle	35°	20°
Optical layout	Transceiver	Mono-static with active co-alignment
Receiver	Sequential **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

References: Reitebuch et al., (2009), J-TECH; Lux et al. (2018), AMT; Marksteiner et al. (2018), Rem. Sens.; Schröder et al., 2007, Appl. Phys. B; Lemmerz et al., 2017, Appl. Opt.

ESA‘s Aeolus Mission
The 2-µm DWL reference system



Parameter	DLR 2-µm DWL [3]
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 scan
Accuracy	**< 0.1 m/s**
Precision (random error)	**~ 1 m/s**

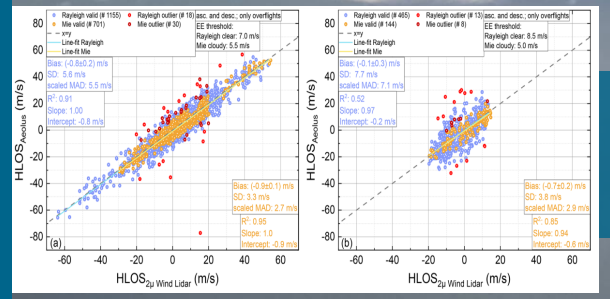
Perfect reference system

References: Witschas et al (2017), J-TECH; Witschas et al. (2022), AMT

OUTLINE

ESA‘s Aeolus mission

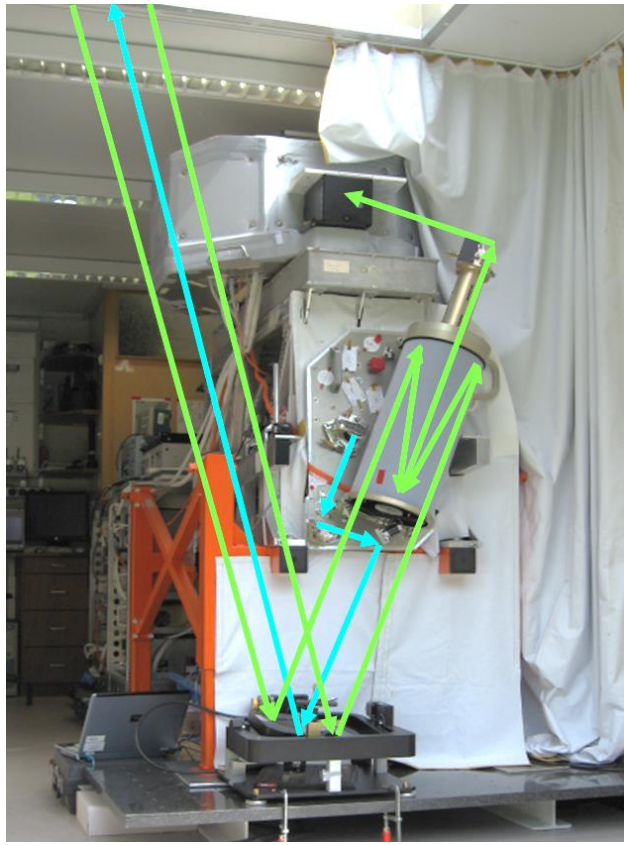
DLR‘s airborne Aeolus CalVal payload



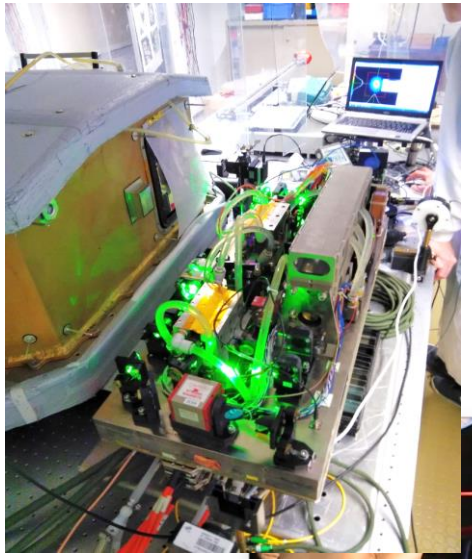
Results from pre- and post launch campaigns

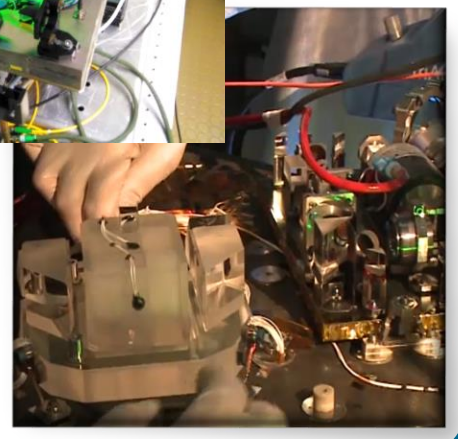
Examples for Aeolus pre-launch CalVal activities at DLR
Use Cases On Ground

Ground campaigns for performance evaluation (since 2005)



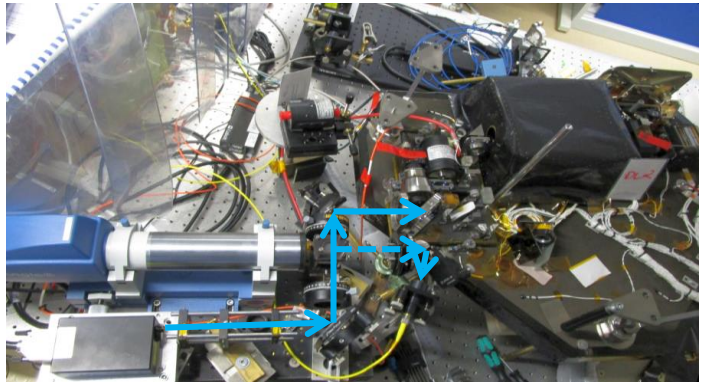
Laser and spectrometer characterization in the lab





Particular case studies

Detection noise characterization



Rayleigh-Brillouin scattering

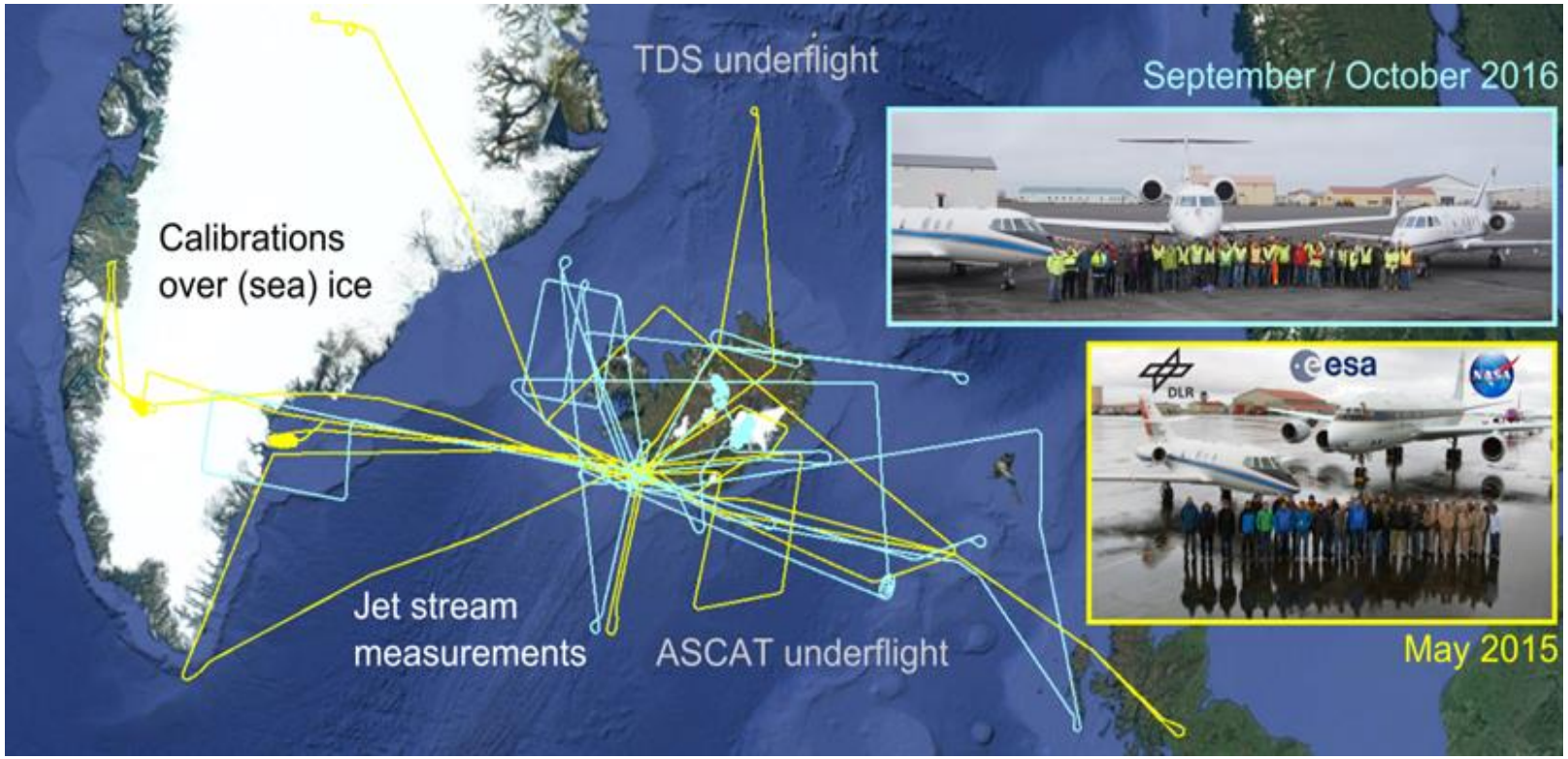
References: Witschas et al (2010), AO, Witschas et al. (2012), AO

Examples for Aeolus pre-launch CalVal activities at DLR
Airborne campaigns (DLR/NASA/CNES)

Aeolus pre-launch campaigns to **test mission procedures and algorithms for Aeolus in-flight** (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 (also in harsh environmental conditions)
- ✓ **More than 150 recommendations for the Aeolus mission derived before launch** (instrument alignment, operations, retrieval algorithms, and calibration)

References: Reitebuch et al. (2009), JAOT; Lemmerz et al. (2017), AO; Lux et al. (2018), AMT; Marksteiner et al. (2018), Rem. Sens.; Witschas et al (2017), J-TECH, Witschas et al., 2021, Opt. Lett.

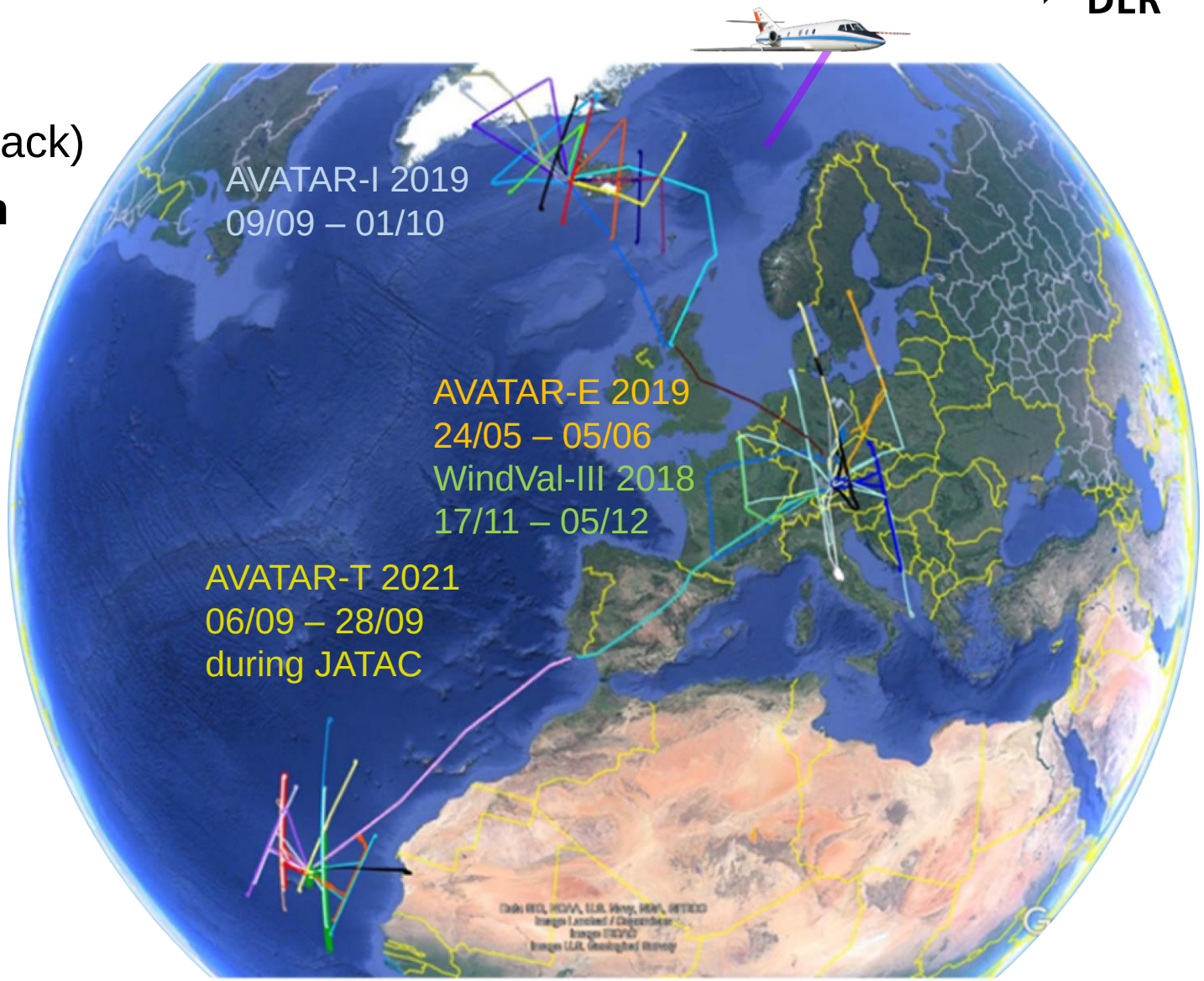
Aeolus validation after launch
Overview

4 airborne campaigns were performed (52 flights, 26400 km along the Aeolus track)

➔ Aeolus performance **characterization under different conditions** (Aeolus signal, atmospheric dynamics, solar background, geographical regions)

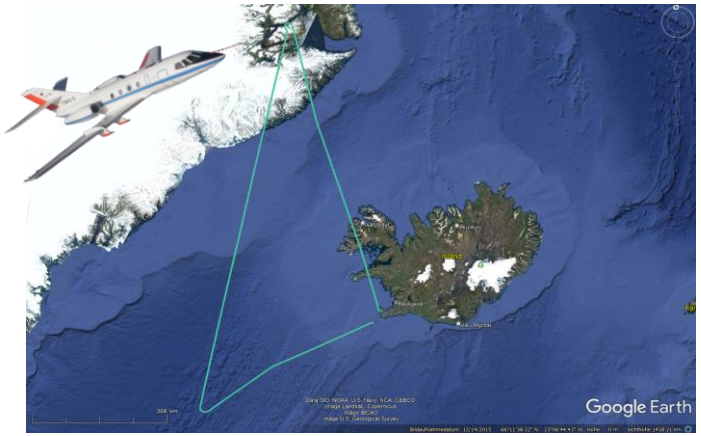
➔ Results for the **processor evolution** (incl. validation of reprocessed data).

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			

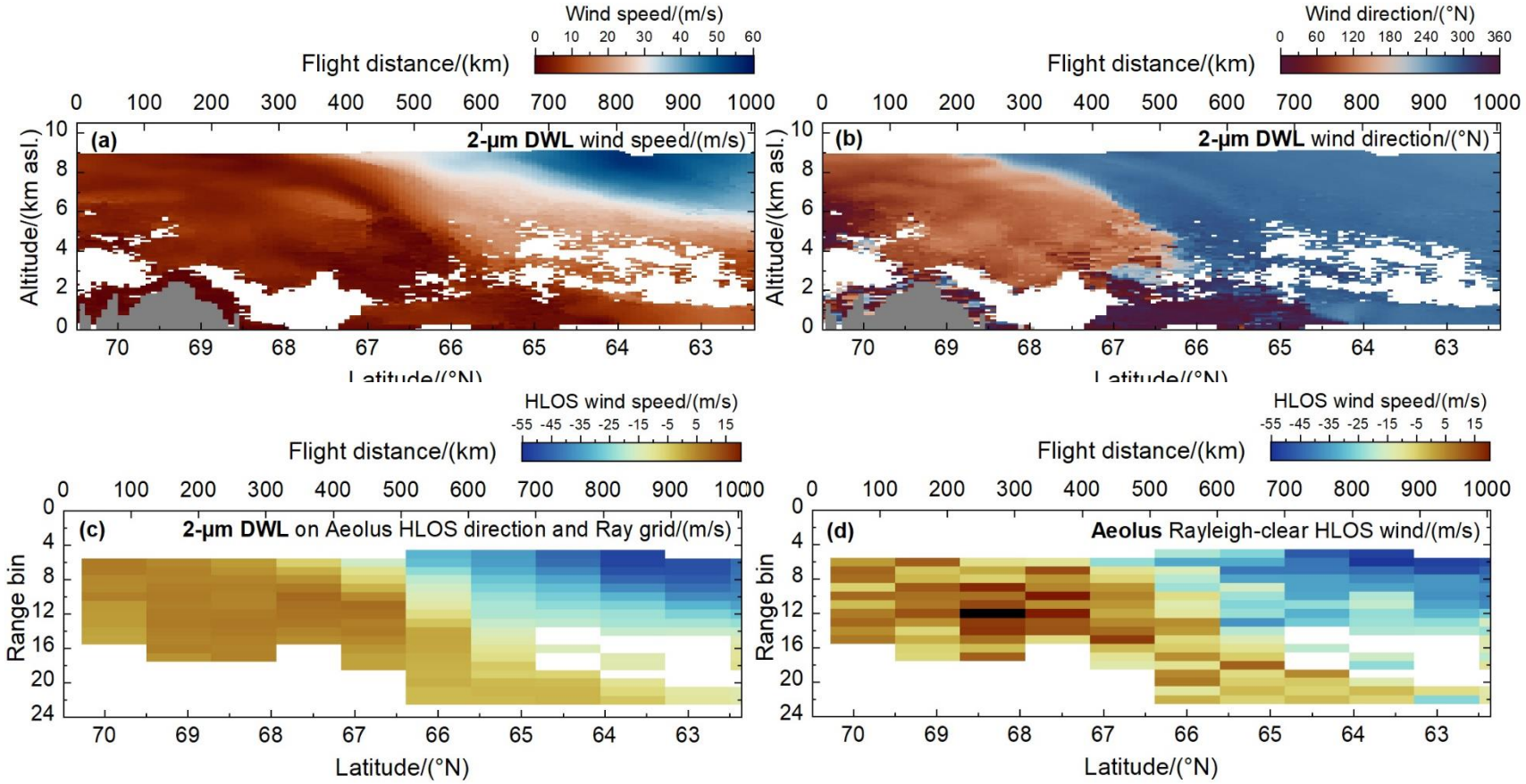


References: Lux et al. (2020), AMT; Witschas et al (2020), AMT; Lux et al. (2022), AMT; Witschas et al (2022), AMT

Comparison of 2-µm DWL and Aeolus data
AVATAR-I underflight performed on 16 Sept 2019



Due to the different horizontal/vertical resolutions of 2-µm DWL measurements (≈ 8.4 km, 100 m) and Aeolus meas. (**≈ 90 km (Rayleigh)** and down to **≈ 10 km (Mie)**, 0.25 km to 2 km), averaging procedures are needed:

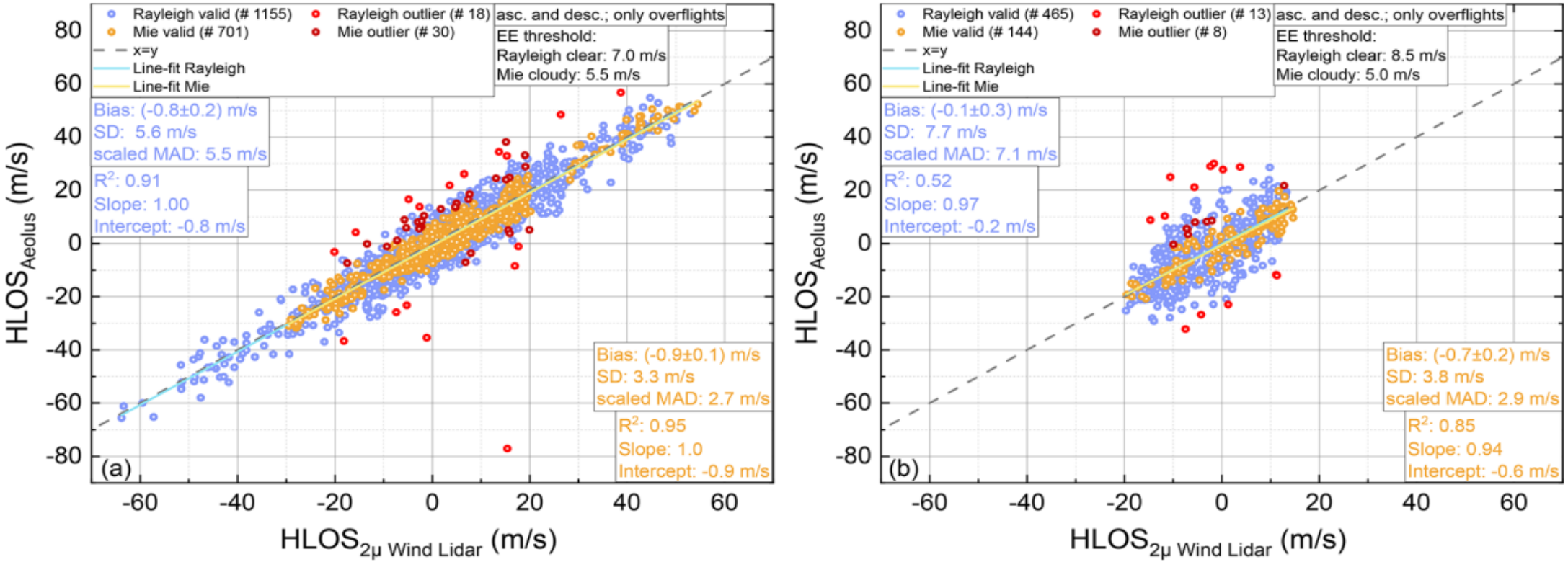


- 2-µm DWL wind speed/direction is **averaged to the Aeolus grid** and afterwards **projected onto the Aeolus horizontal LOS**
- The Aeolus HLOS winds (**valid** Rayleigh-clear and Mie-cloudy winds) are extracted for areas of valid 2-µm DWL measurements
- Beforehand, the Aeolus data is quality controlled by means of an **estimated error**

References: Witschas et al (2020); Witschas et al (2022), AMT

Statistical comparison of Aeolus and 2-µm DWL observations

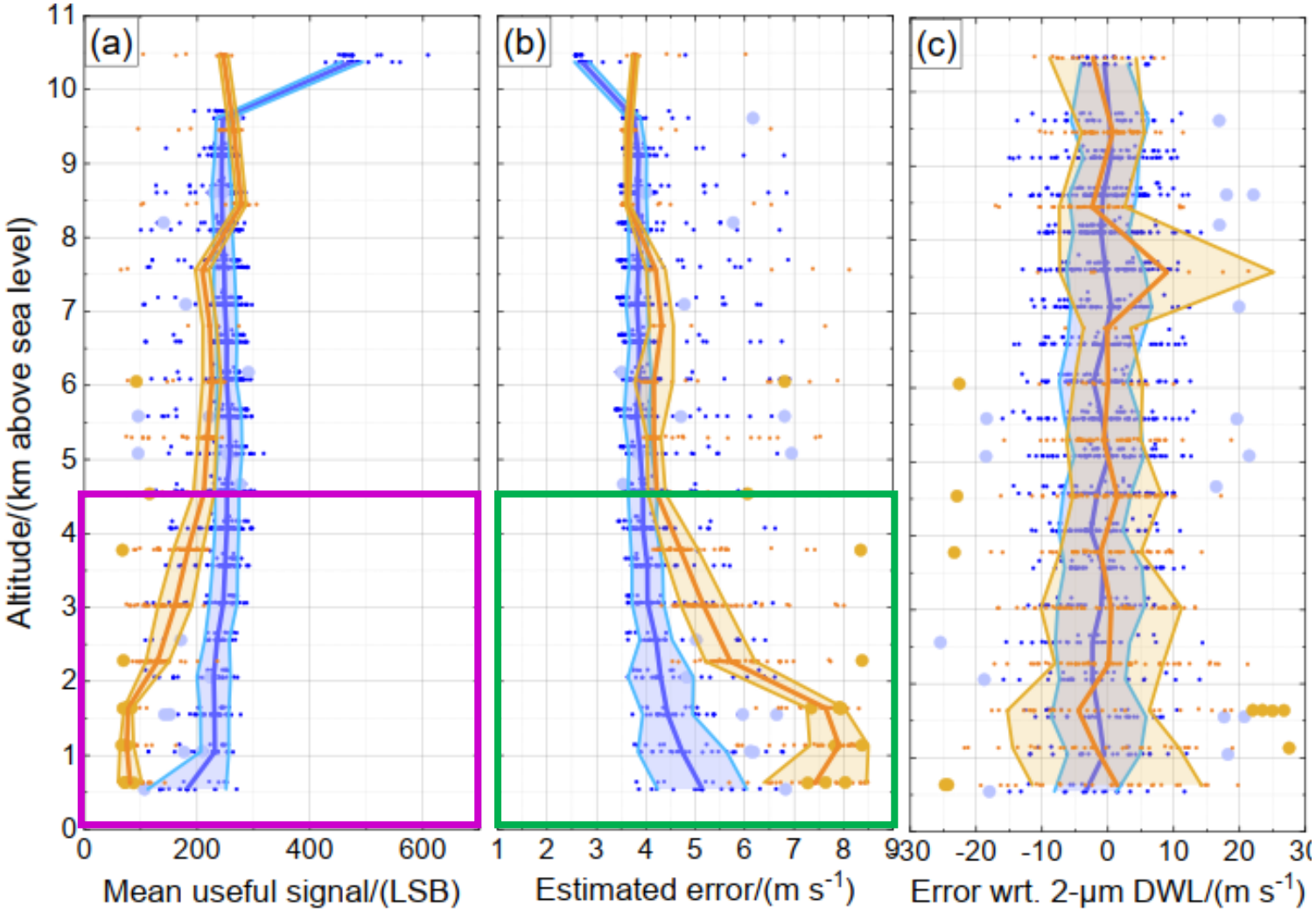
From the AVATAR-I (North Atlantic) and the AVATAR-T (Tropics) campaign



- Mean **systematic error:** **-0.8 ± 0.2 m/s** (Rayleigh-clear) and **-0.9 ± 0.1 m/s** (Mie-cloudy) for AVATAR-I and **-0.1 ± 0.3 m/s** (Rayleigh-clear) and **-0.7 ± 0.2 m/s** (Mie-cloudy) for AVATAR-T → **close to the specified mission requirement of 0.7 m/s.**
- Mean **random error** for **Rayleigh-clear winds** (**5.5 m/s** AVATAR-I and **7.1 m/s** for AVATAR-T) is significantly larger than specified (**2.5 m/s**), which is due to the lower signal levels (initial loss, misalignment and laser-induced contamination).
- The mean **random error** of the **Mie-cloudy winds** (**2.7 m/s** for AVATAR-I and **2.9 m/s** for AVATAR-T) is close to the specs.

References: Witschas et al (2020); Witschas et al (2022), AMT

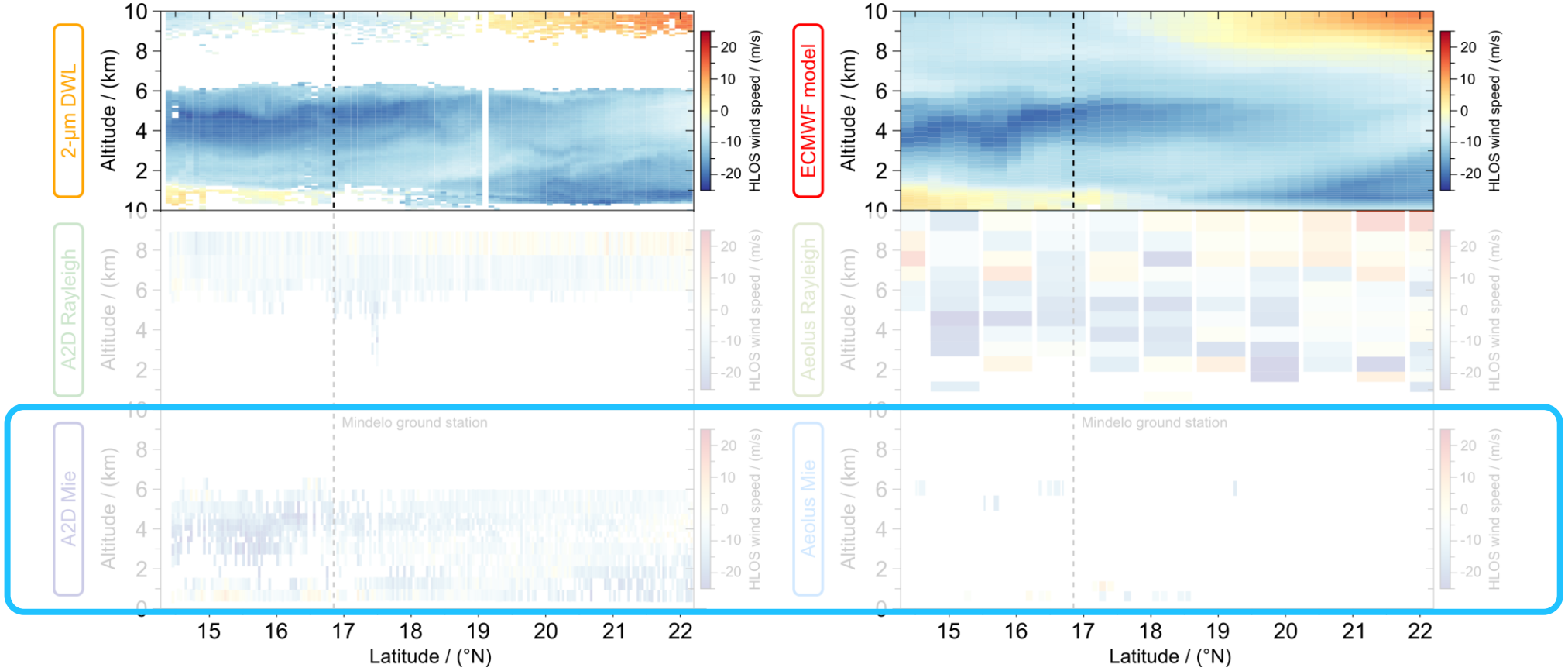
Height dependency of L2B Rayleigh-clear winds
For the AVATAR-I and the AVATAR-T data set



- Signal levels during AVATAR-T were lower compared with AVATAR-I.
- This is especially true for lower altitudes due to the extinction of aerosols present in the Saharan Air Layer.
- The estimated error shows larger values in regions of lower signal levels (as expected)
- The systematic error (wrt. to the 2-µm DWL) shows no altitude dependency → proper calibration is used

References: Witschas et al (2022), AMT

Aeolus retrieval improvements based on A2D data
Aeolus underflight on 10 September 2021 (AVATAR-T)

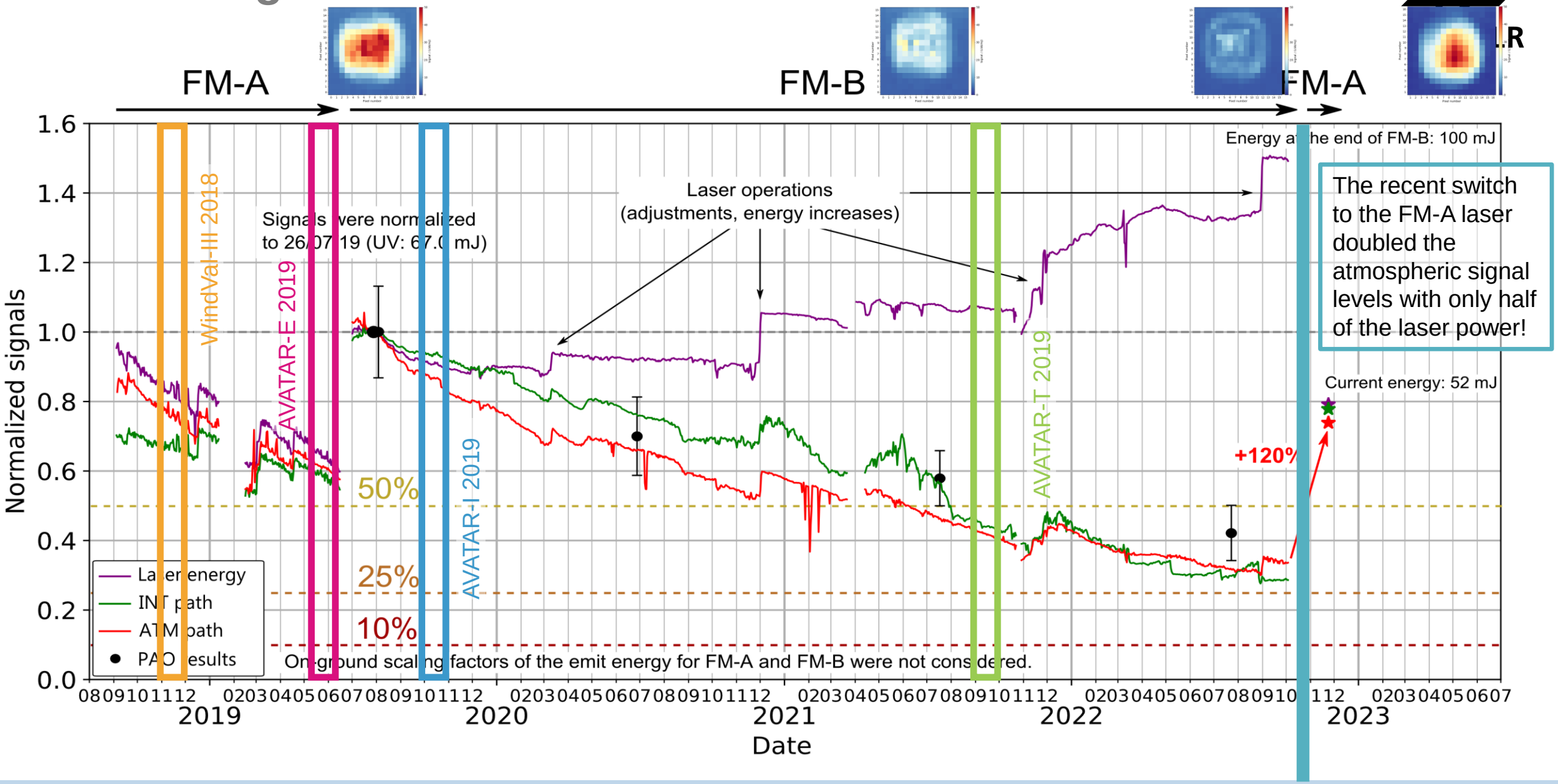


- The comparison of A2D and Aeolus Mie-cloudy winds reveals significant differences regarding the data coverage → **potential for Aeolus algorithm improvement** (currently under investigation)

References: Lux et al (2022), HPLSA

Aeolus signal evolution over the mission

Laser beam monitoring images over the mission lifetime derived from Mie receiver channel data



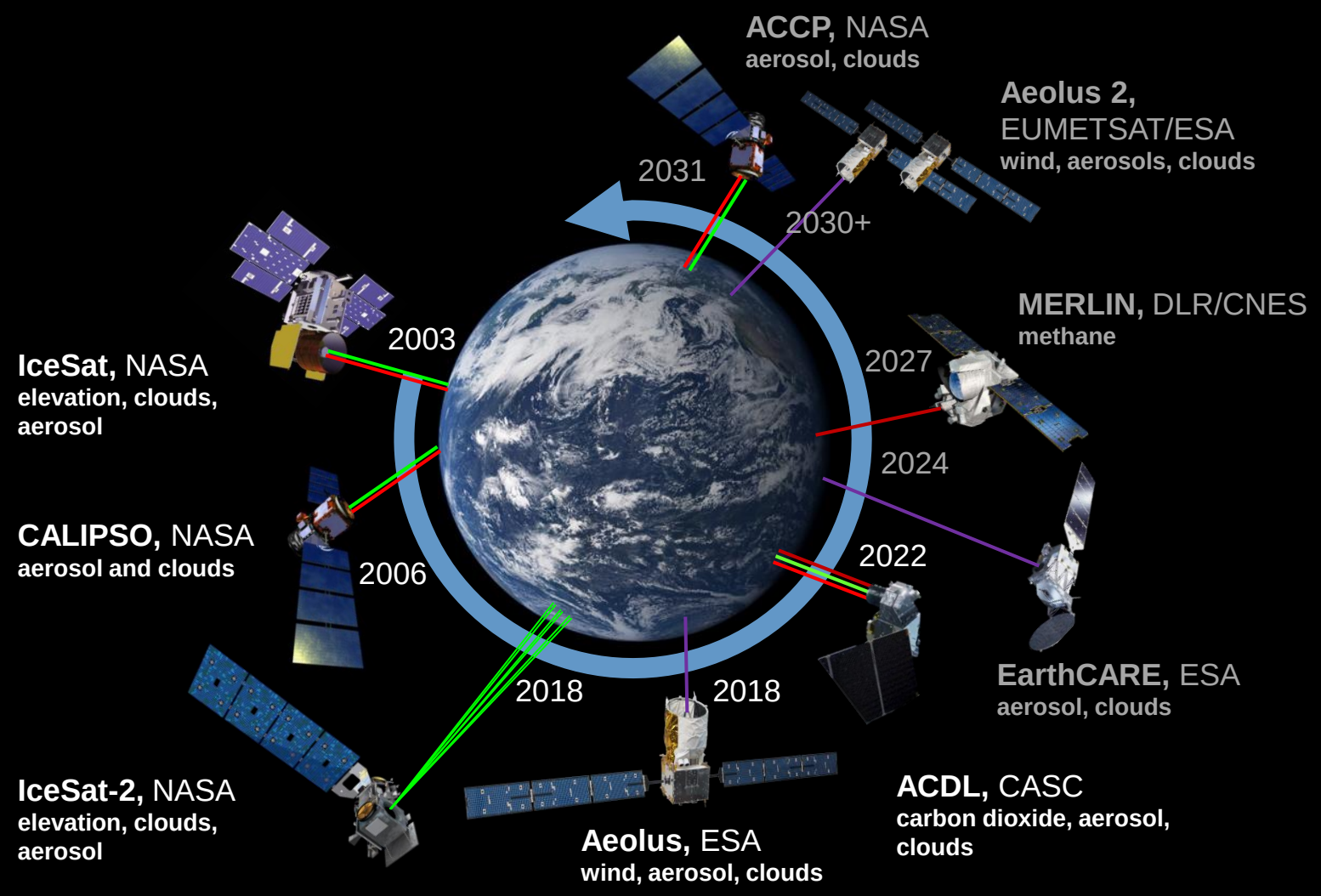
The recent switch to the FM-A laser doubled the atmospheric signal levels with only half of the laser power!

References: Figure by O. Lux, DLR

Summary

- **Aeolus is the first European lidar mission and the first wind lidar in space** operating for > 4 years. It has successfully demonstrated the technology readiness of complex lidars as well as the positive impact on numerical weather prediction (main mission goals achieved).
- **An airborne Aeolus CalVal payload was developed at DLR** based on an Aeolus demonstrator instrument (A2D) and a reference lidar. This payload has been operating since 2005 and **contributed to the success of Aeolus both, before and after launch** by for instance algorithm development, operation/calibration procedures, and wind product characterization.
- **After launch, DLR performed 4 airborne CalVal campaigns** (52 flights/192 flight hours) and revealed that:
  - the **mean systematic error meets the mission requirements** (**< 0.7 m/s**) (Mie & Ray.)
  - the **mean random error of Mie winds almost meets the mission requirements** (**< 2.5 m/s**) whereas it is **significantly larger (up to 7 m/s) for Rayleigh winds** (caused by initial loss, misalignment and laser-induced contamination).
- During the recent ESA ministerial council meeting**, the founding for the first phases of an Aeolus follow-on mission was approved** (2030+, two satellites, > 5 years duration, similar technology with modifications).

Outlook


ACCP, NASA
aerosol, clouds
Aeolus 2,
EUMETSAT/ESA
wind, aerosols, clouds
2031
2030+
MERLIN, DLR/CNES
methane
2027
2024
2022
EarthCARE, ESA
aerosol, clouds
ACDL, CASC
carbon dioxide, aerosol,
clouds
2018
2018
Aeolus, ESA
wind, aerosol, clouds
IceSat-2, NASA
elevation, clouds,
aerosol
2006
CALIPSO, NASA
aerosol and clouds
2003
IceSat, NASA
elevation, clouds,
aerosol


AVATARE
esa
DLR
Aeolus Validation Through Airborne Lidars in Europe