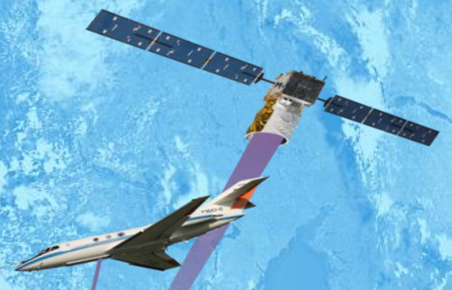

ESA's Aeolus Mission: Unveiling Laser and Spectrometer Performance in the First Wind Lidar in Space

B. Witschas[1], O. Lux[1], C. Lemmerz[1], O. Reitebuch[1], M. Vaughan[2], the DISC team

Optica Laser Congress and Exhibition, 19 – 23 October 2025, Prague, Czech Republic

[1] Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institute of Atmospheric Physics, Münchener Str. 20, 82234 Oberpfaffenhofen, Germany

[2] Optical & Lidar Associates (OLA), Buckinghamshire, HP14 3PF, UK

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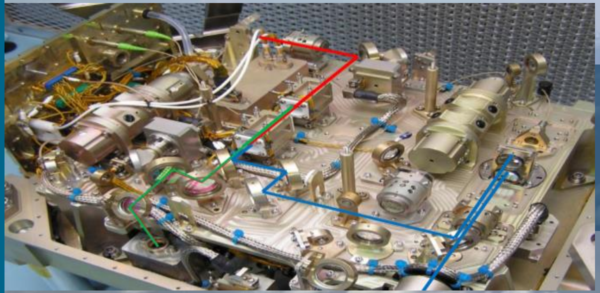
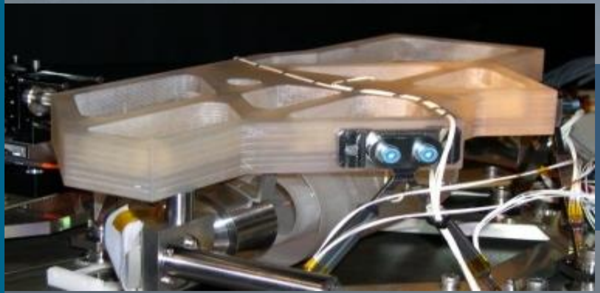
ESA‘s Aeolus mission



Setup and performance of the laser

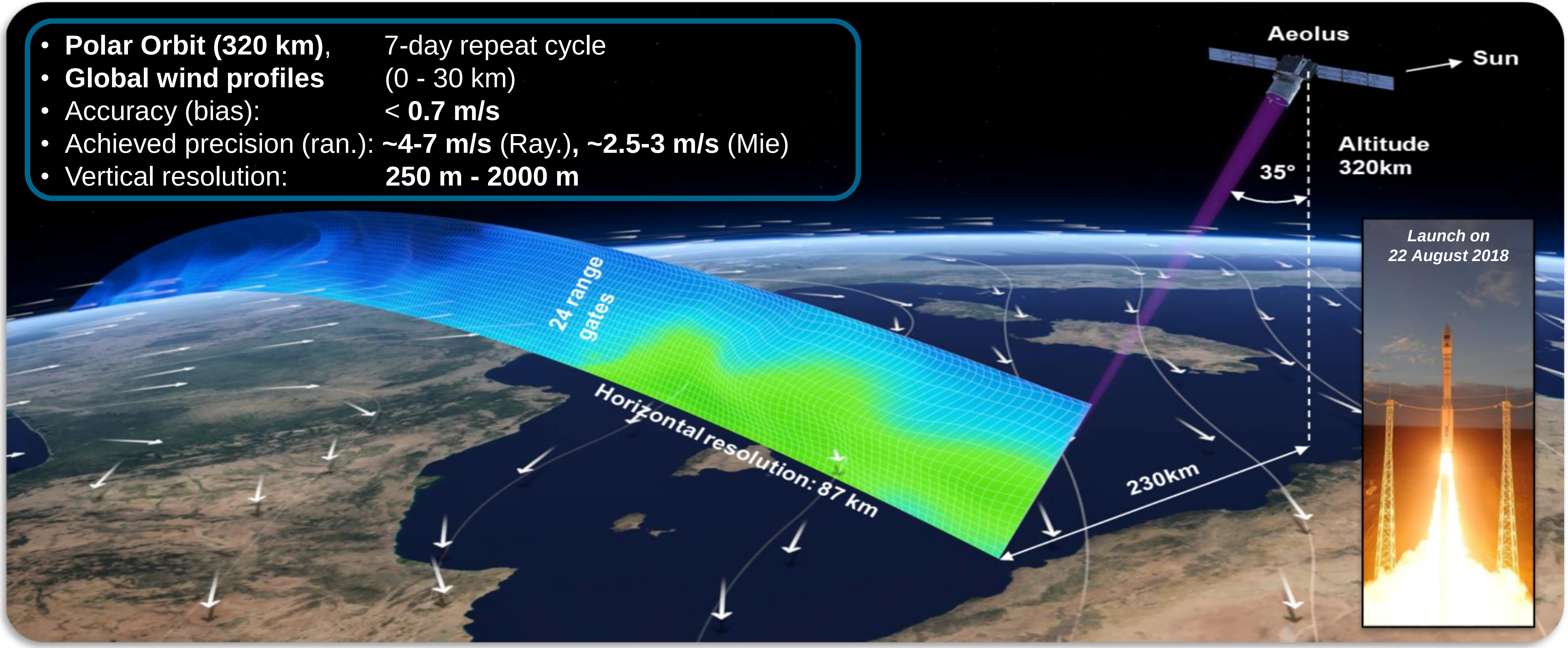


Setup and performance of the spectrometers

Aeolus – the first spaceborne wind lidar (2018 – 2023)

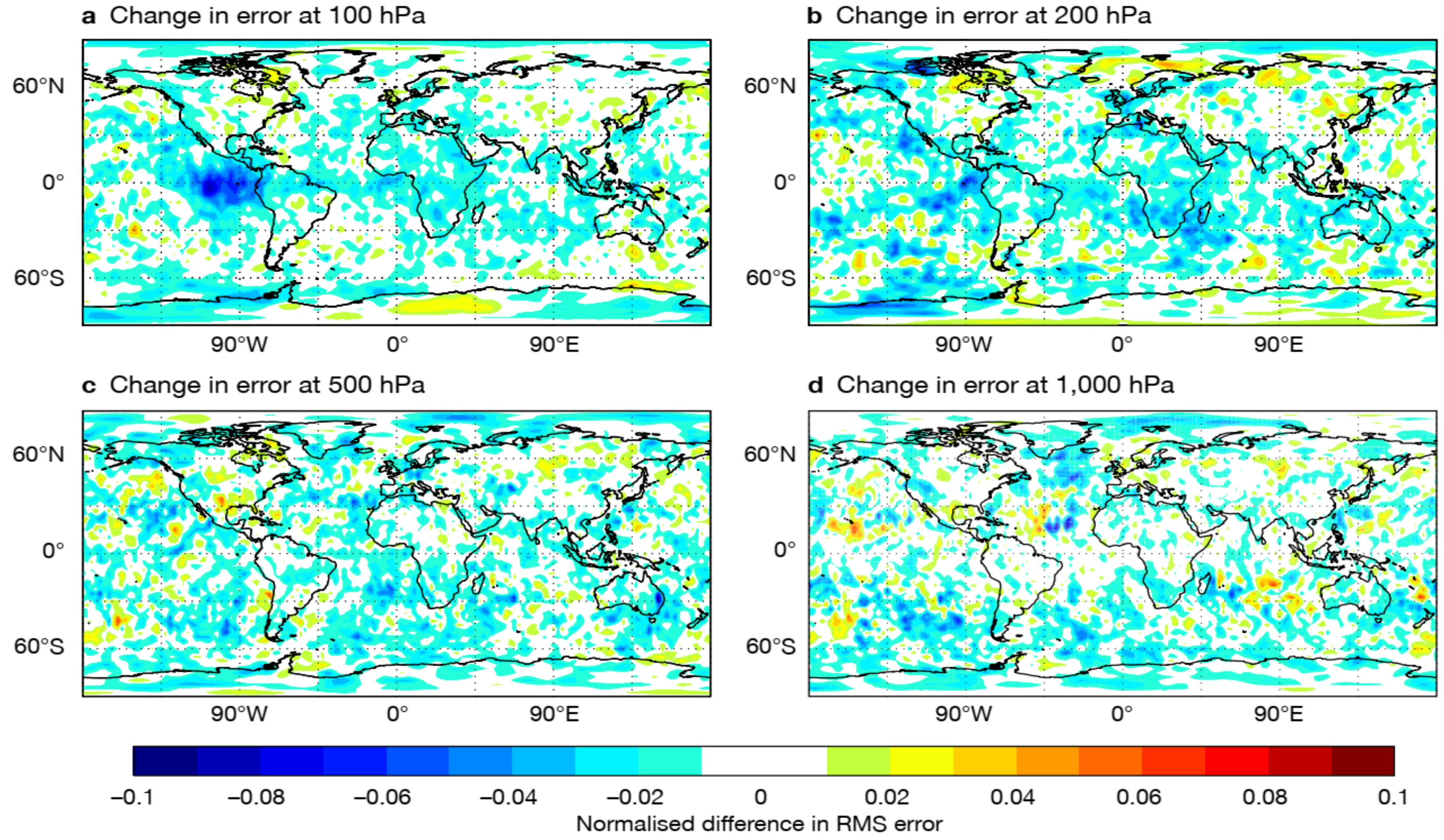
The primary goals of Aeolus were the **precise global wind profile measurements** to improving numerical weather prediction and **technology demonstration**.

- **Polar Orbit (320 km)**, 7-day repeat cycle
- **Global wind profiles** (0 - 30 km)
- Accuracy (bias): < **0.7 m/s**
- Achieved precision (ran.): **~4-7 m/s** (Ray.)**, ~2.5-3 m/s** (Mie)
- Vertical resolution: **250 m - 2000 m**



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

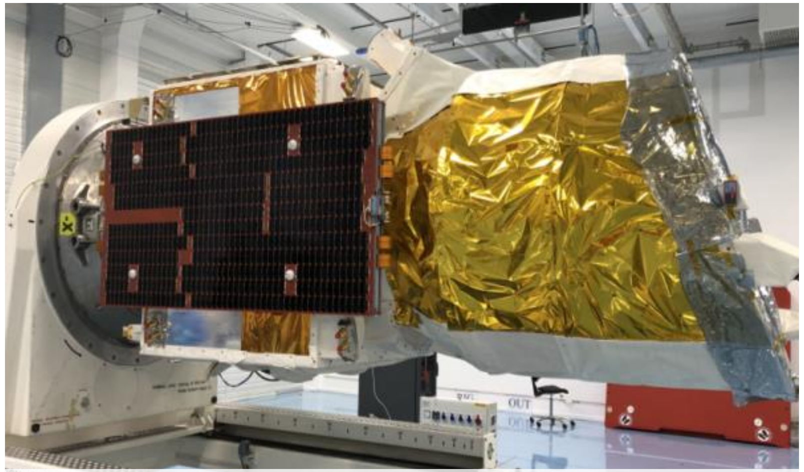
Positive impact on numerical Weather forecast



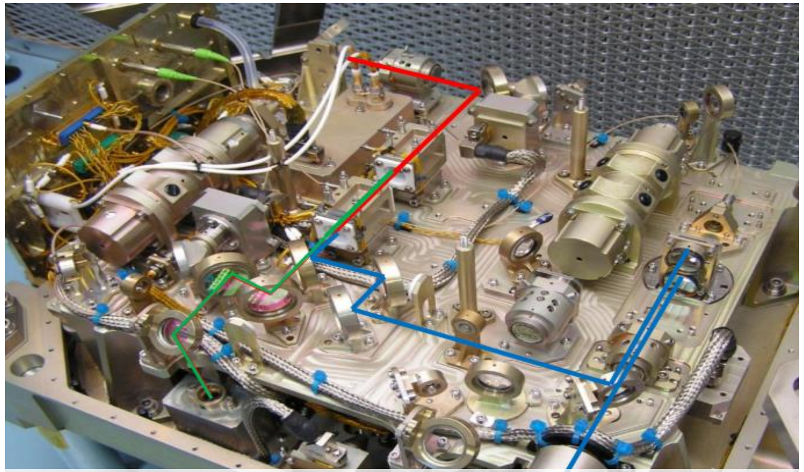
ECMWF assessment (reprocessed data, 15-month period in 2019/2020), **reveals a positive impact** improving **wind**, **temperature** and **humidity** forecasts by up to 1–2 % (lower stratosphere, medium forecast range), and little smaller but still statistically significant at lower altitudes.

References: Rennie et al., ECMWF, 2022

ESA‘s Aeolus Mission
A technological challenge



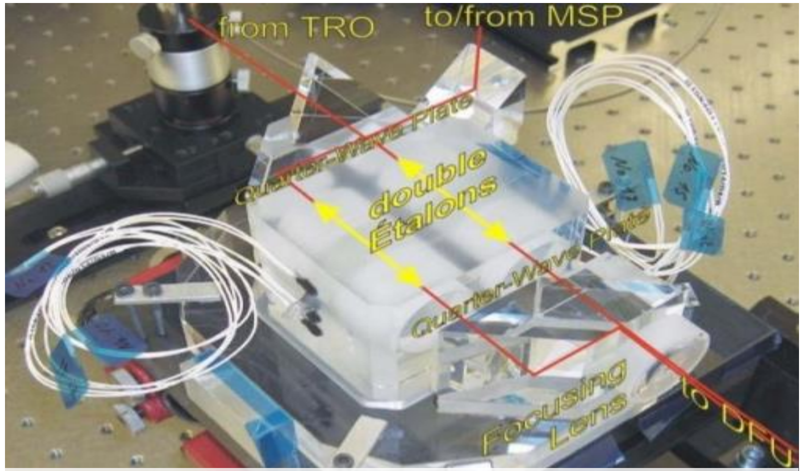
Aeolus satellite



ALADIN laser transmitter

Fig. credits Airbus DS

Mie spectrometer



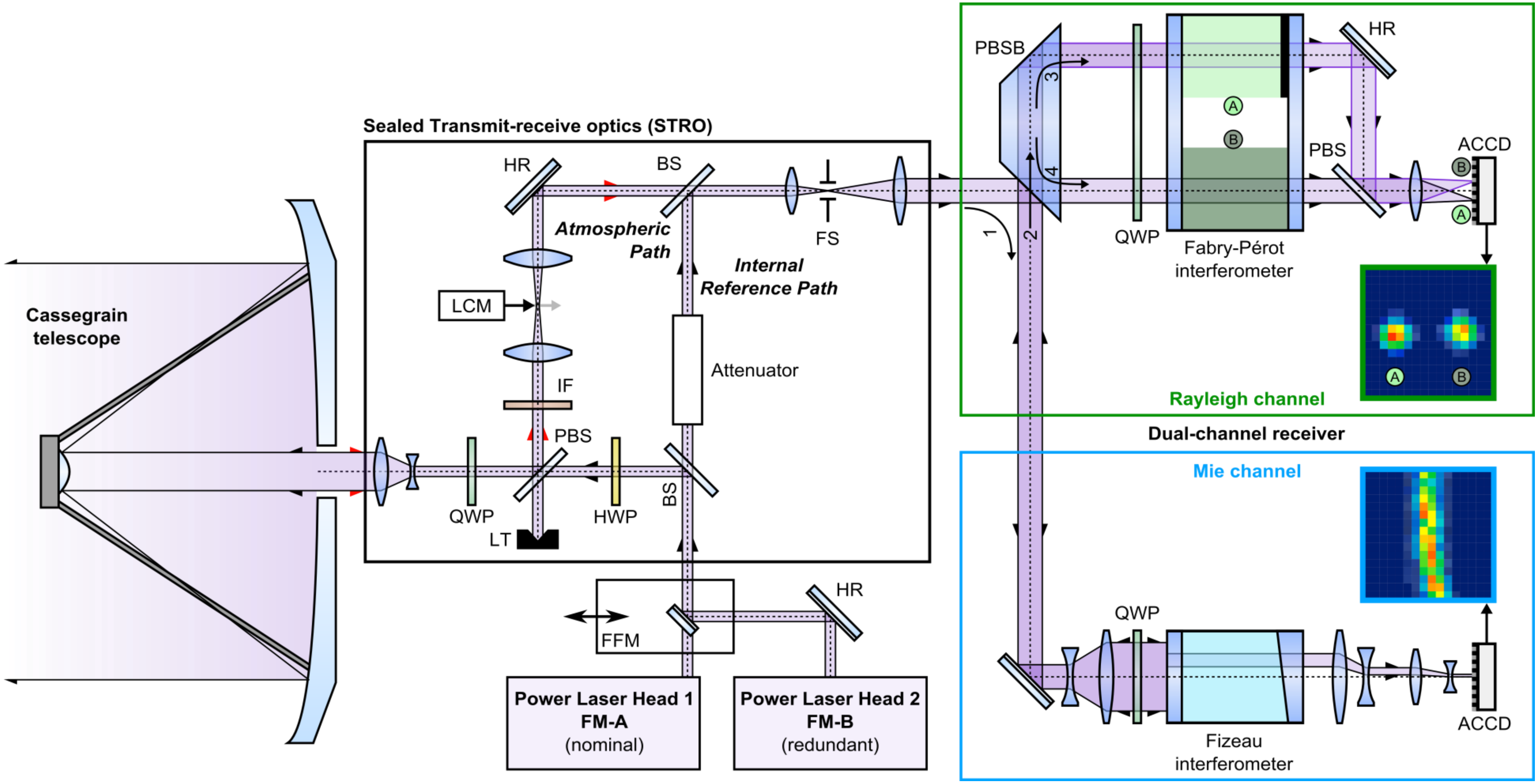
Rayleigh spectrometer

- **First European lidar mission** after 20 years of challenging development
- **First spaceborne high-power UV laser** with stringent requirements on frequency stability operated in vacuum
- **Sequentially arranged spectrometers** to “recycle” photons
- **New detector types used** (accumulating charged coupled devices)

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

ALADIN instrument design

- **UV** laser transmitter, **1.5 m telescope** and **dual-channel** receiver
- **Complementary Rayleigh and Mie channels** for sensing the Doppler shift from molecules and particles (aerosols, clouds)
- **Measurement of the Doppler frequency shift with accuracy of 10^{-8}** in order to achieve wind speed accuracy of 1 m/s



Doppler equation:

$$\Delta f = 2 f_0 \frac{v_{\mathrm{LOS}}}{c}$$

relative Doppler shift:

$$\Delta f / f_0 \approx 10^{-8}$$

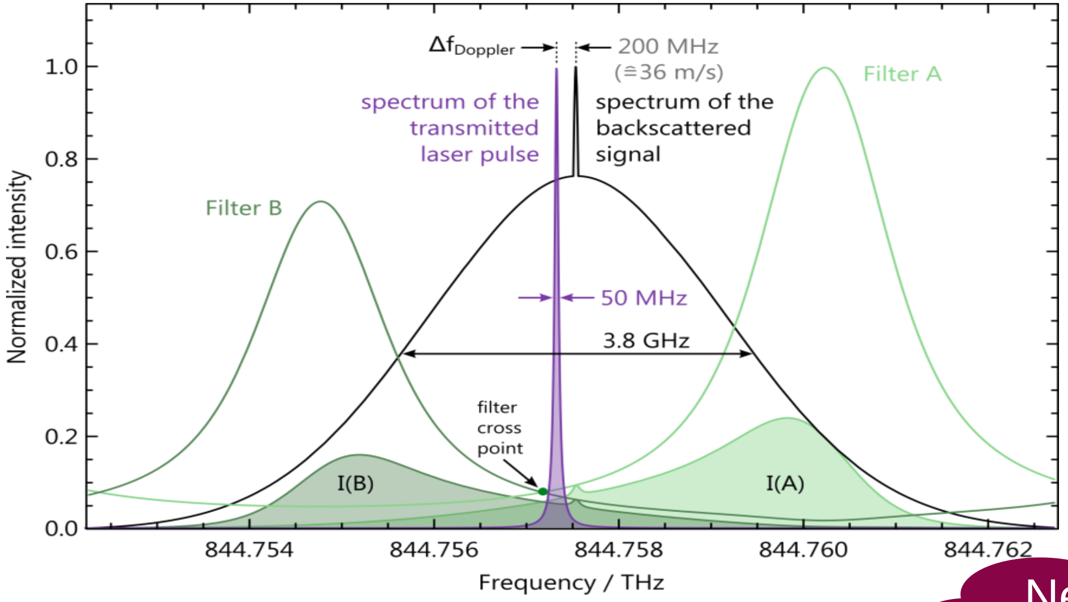
1 m/s (Line-of-sight)
~ 5.64 MHz ~ 2.37 fm

ESA‘s Aeolus Mission
Aeolus measurement principle

Winds measured from **molecular backscattered light**

(Rayleigh-clear winds)

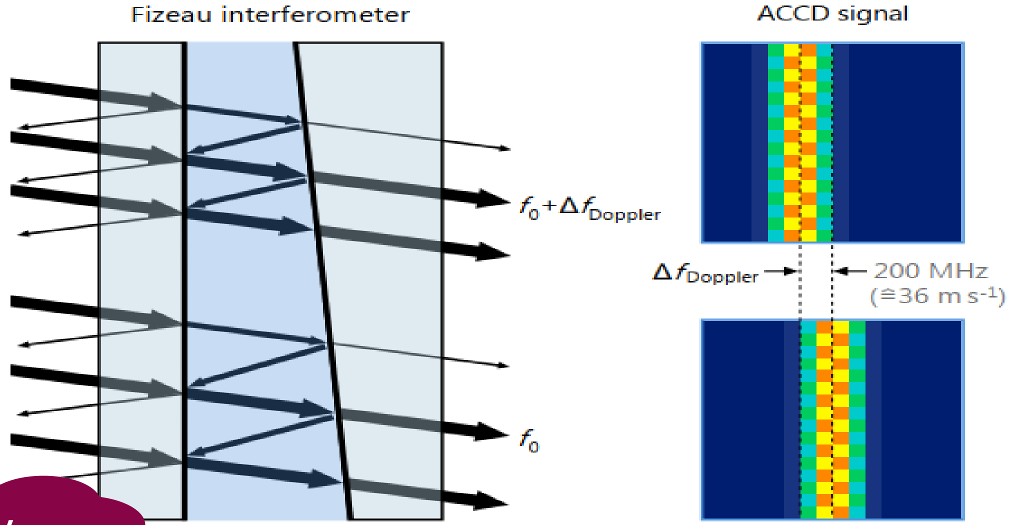
based on the so-called double-edge technique.



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

(Mie-cloudy winds)

based on the so-called fringe imaging technique.



Next talk by C. Lemmerz

Simple measurement principle but complex technology and high accuracy required on both laser and spectrometer **(intensive monitoring and CalVal activities throughout the mission).**

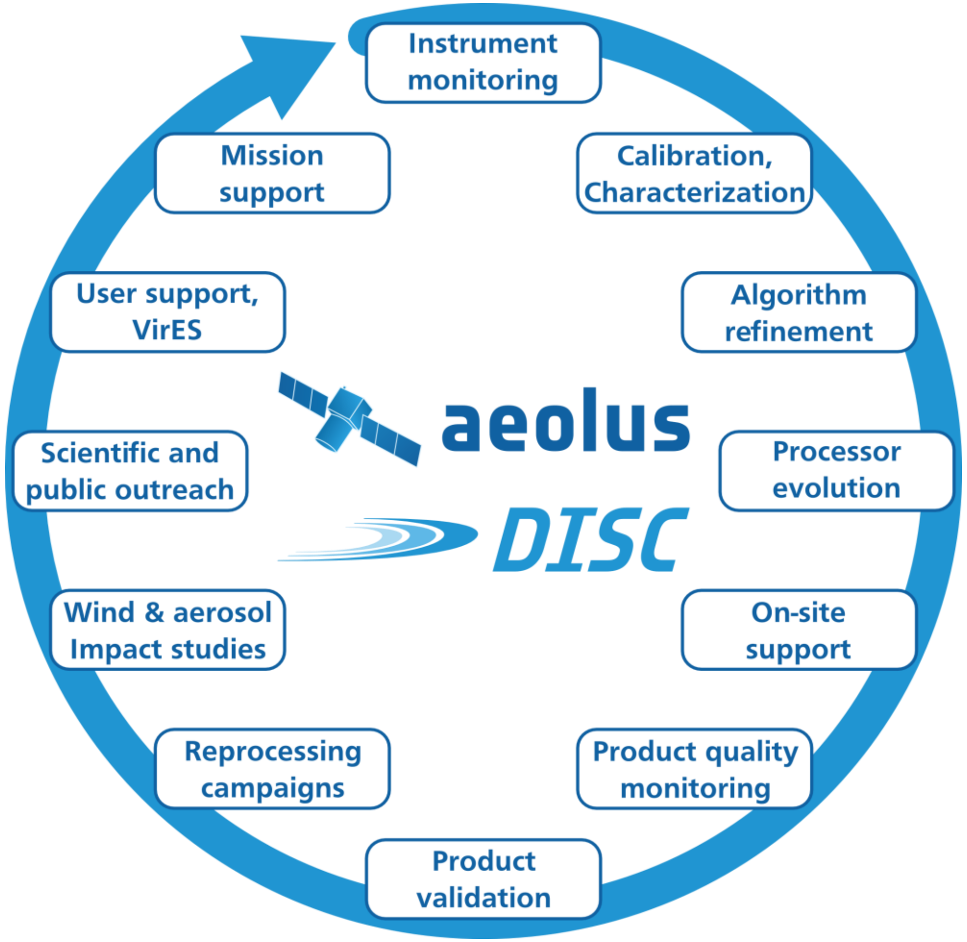
References: Lux et al., AMT, 2018

The Aeolus Data Innovation and Science Cluster - DISC

Oliver Reitebuch, Stefanie Knobloch, Christian Lemmerz, Oliver Lux, Uwe Marksteiner, *Nafiseh Masoumzadeh*, *Fabian Weiler*, Benjamin Witschas, Vittoria Cito Filomarino, *Isabell Krisch*, Markus Meringer, Karsten Schmidt, Dorit Huber, Ines Nikolaus, Frédéric Fabre, Michael Vaughan, Katja Reissig, *Alain Dabas*, *Thomas Flament, Adrien Lacour, Jean-Francois Mahfouf, Ibrahim Seck*, Saleh Abdalla, *Lars Isaksen*, Michael Rennie, Angela Benedetti, Will McLean, Karen Henry, Dave Donovan, Jos de Kloe, Gert-Jan Marseille, Ad Stoffelen, Ping Wang, Gerd-Jan van Zadelhoff, Diko Hemminga, *Gaetan Perron, Sebastian Jupin-Langlois*, *Bas Pijnacker Hordijk*, Filippo Tagliacarne, *Marcella Veneziani*, *Simone Bucci*, Giacomo Gostinicchi, Marco Galli, Massimo Cardaci, Sebastian Bley, Dimitri Trapon, *Alexander Geiss*, *Thomas Kanitz, Anne-Grete Straume*, Eliana Barbera, Denny Wernham, Trismono Krisna, *Jonas von Bismarck, Massimo Romanazzo*, Stefano Aprile, Timon Hummel and Tommaso Parrinello.

- DISC was kicked-off 2019 (until 2028) **with teams cooperating since 2003** and funded by ESA
- **14 international partners** with **≈40 scientists** and engineers coordinated by DLR
- **Broad range of experts** and **strong links to all ESA entities**, **space industry** and **science community**

DISC Meeting at ESRIN in Frascati March 2024



References: Lux et al., AMT, 2018

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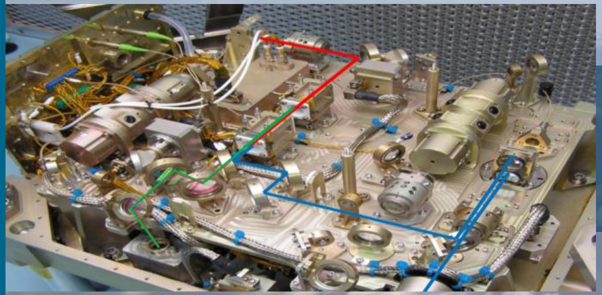
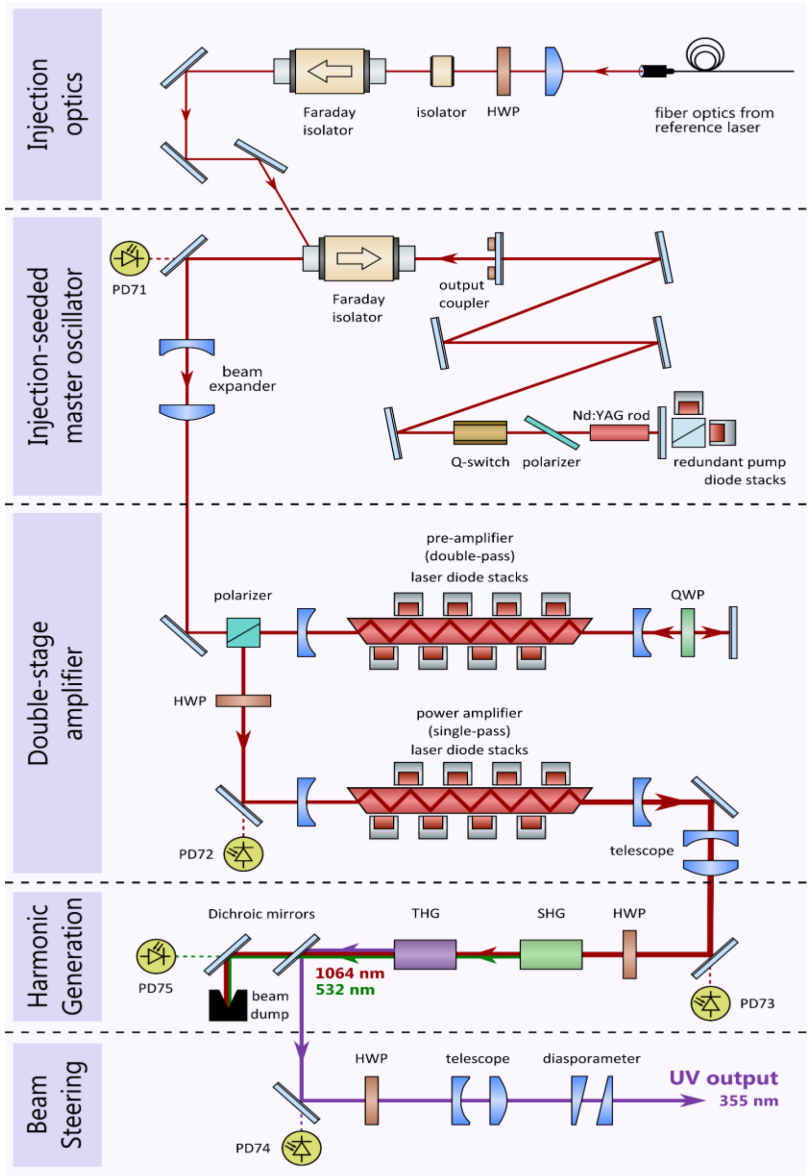


Setup and performance of the laser

Laser design and specifications

DLR



- **Injection-seeded and frequency-tripled master oscillator power amplifier Nd:YAG system** at 355 nm wavelength (by *Leonardo*)
- **Monitoring of the laser status and performance** based on photodiodes, temp. sensors, receiver raw data
- **Strong expertise gained from airborne demonstrator** to support laser activities, anomaly investigations. **(talk by C. Lemmerz)**

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applied optics

Performance of the ultraviolet laser transmitter during ESA's Doppler wind lidar mission Aeolus

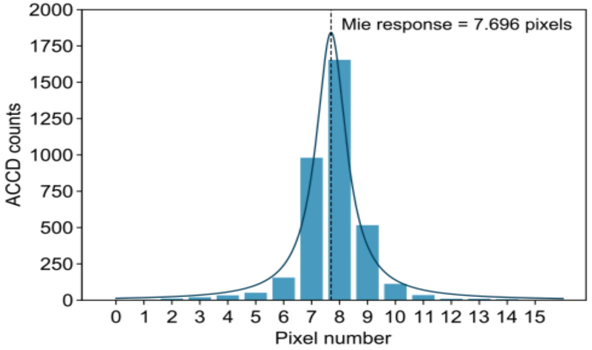
Oliver Lux,[1,*] Christian Lemmerz,[1] Valeria De Sanctis,[2] Paolo Bravetti,[3,4] Denny Wernham,[4] Trismono Candra Krisna,[4] Tommaso Parrinello,[5] and Oliver Reitebuch[1]

Parameter	Value
Type	Frequency-tripled Nd:YAG
Laser wavelength	354.8 nm
Pulse repetition rate	50.5 Hz
Pulse energy (measured with PD74)	FM-A: 40 to 70 mJ; FM-B: 60 to 100 mJ (182 mJ over 1 day)
Pulse energy correction factors for PD74	FM-A: 0.7663; FM-B: 0.9409
Pulse width (FWHM)	20 ns
Spectral width (FWHM)	< 50 MHz
Frequency stability (rms over 540 pulses)	< 12 MHz (< 7 MHz at optimized cavity control setting)
Beam diameter	< 6.2 mm
Beam divergence (full angle)	< 600 µrad
Operation time in space	FM-A: 15 months; FM-B: 41 months
Total number of pulses	FM-A: 1.9 Gigashots; FM-B: 5.3 Gigashots

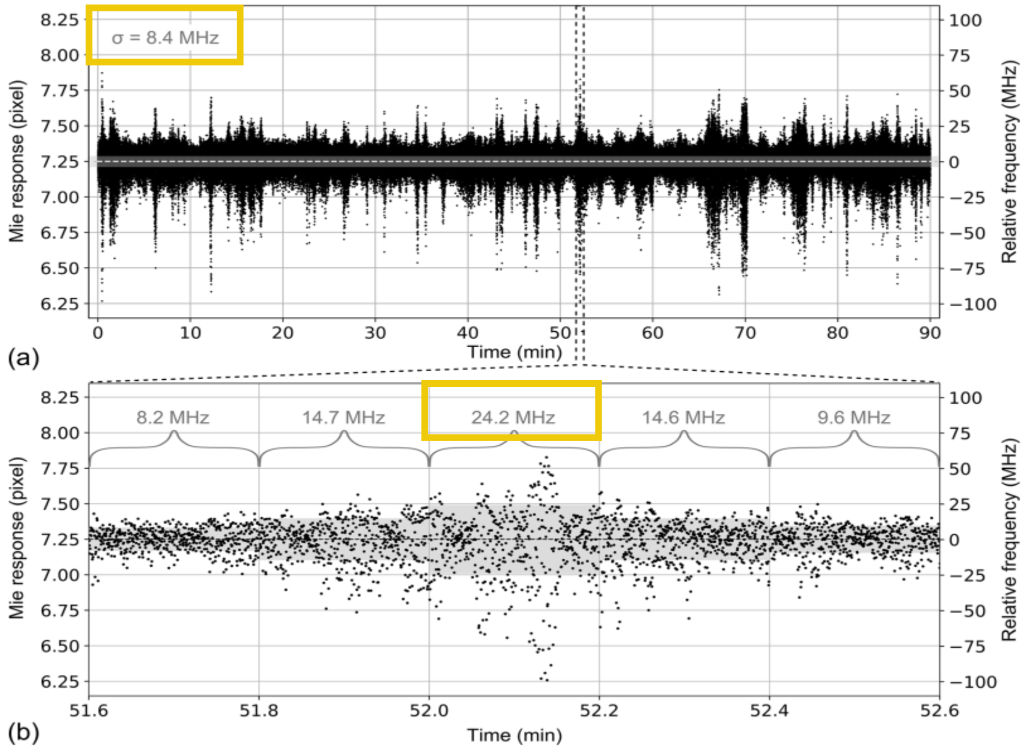
Laser frequency stability characterization

ALADIN as wavemeter

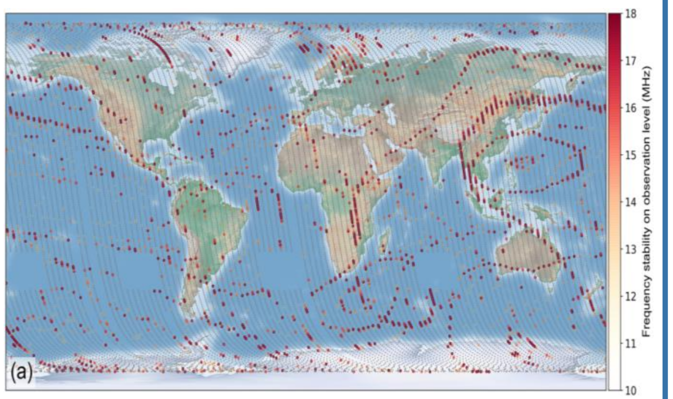
The internal reference signal together with the Fizeau interferometer are used as a wavemeter
→ **frequency stability from shot-to-shot**



Laser frequency fluctuations along one orbit



Wind observations with enhanced frequency noise

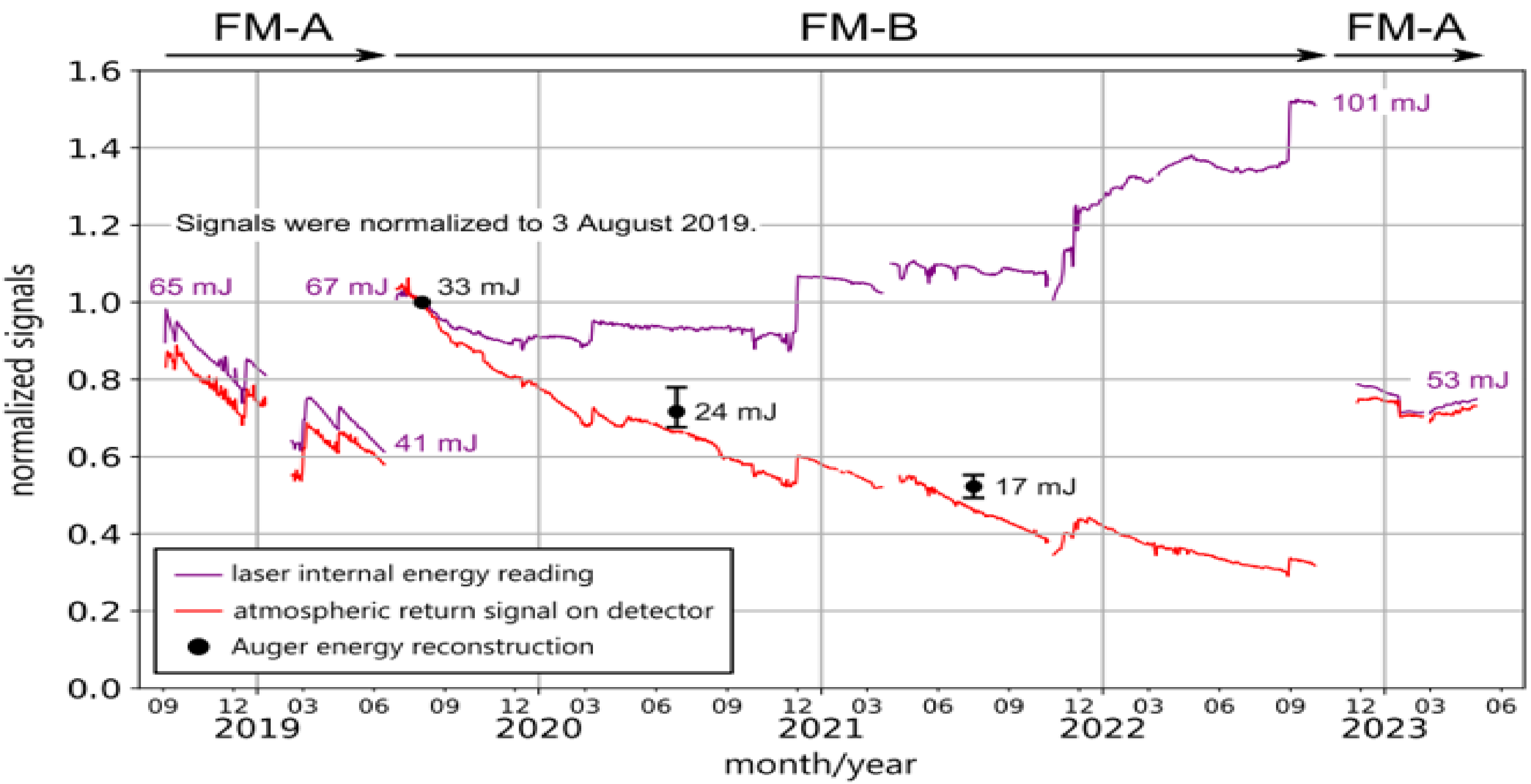


- Dependency on geolocation
  → regions with critical rotation speeds of the satellite's reaction wheels
  → micro-vibrations

- Frequency stability is **better than 10 MHz**
- Critical rotation speeds of the satellite's reaction wheels led to enhanced noise of up to 150 MHz (pulse to pulse) and 30 MHz rms, with no obvious impact on the wind error (small percentage of wind measurements).

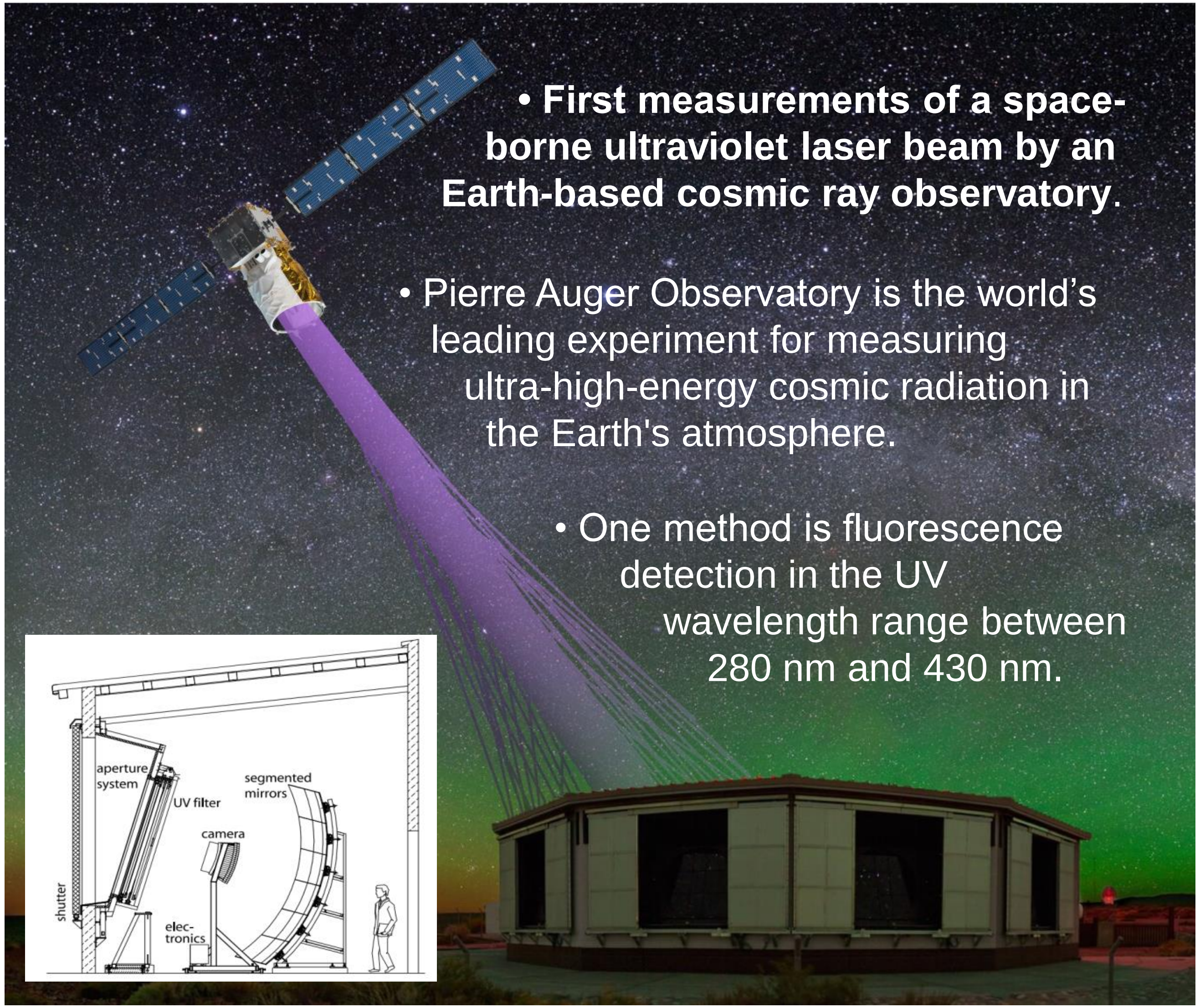
- Lux et al. AMT, 2021: "ALADIN laser frequency stability and its impact on the Aeolus wind error".

Aeolus signal evolution throughout the mission



- **Strong signal loss by 70%** between 2019 and 2022 was caused by laser-induced contamination and/or damage on the optics that guide the redundant laser output onto the common emission path.

Measurements at the Pierre Auger Observatory
Observing ALADIN’s UV laser beam on ground



- **First measurements of a space-borne ultraviolet laser beam by an Earth-based cosmic ray observatory.**
- Pierre Auger Observatory is the world’s leading experiment for measuring ultra-high-energy cosmic radiation in the Earth's atmosphere.
- One method is fluorescence detection in the UV wavelength range between 280 nm and 430 nm.

- **ALADIN laser beam was visible once a week during SH winters** when passing the observatory in Argentina which consists of 4 sites with 6 fluorescence detectors each.
- **Geometrical reconstruction of the laser beam** after being scattered by molecules when passing through the atmosphere (similar to fluorescent light from cosmic-ray air showers).

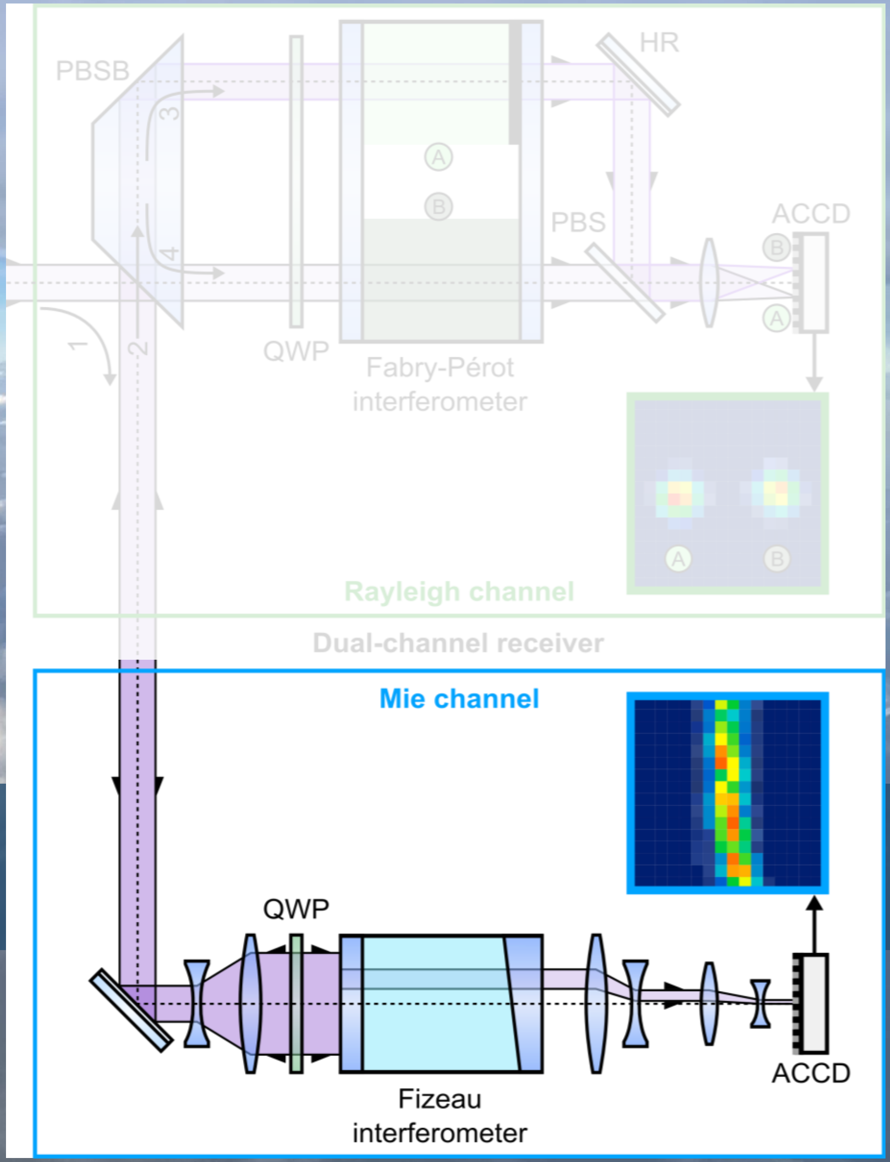
Data provided very valuable information:

- Correction of an processor error to reduce the offset between assumed and measured ground track from 6.8 km to 0.8 km.
- Confirmation that the signal is already lost between laser output and the telescope.

References: The Pierre Auger Collaboration et al.: Ground observations of a space laser for the assessment of its in-orbit performance, Optica, 2024

OUTLINE

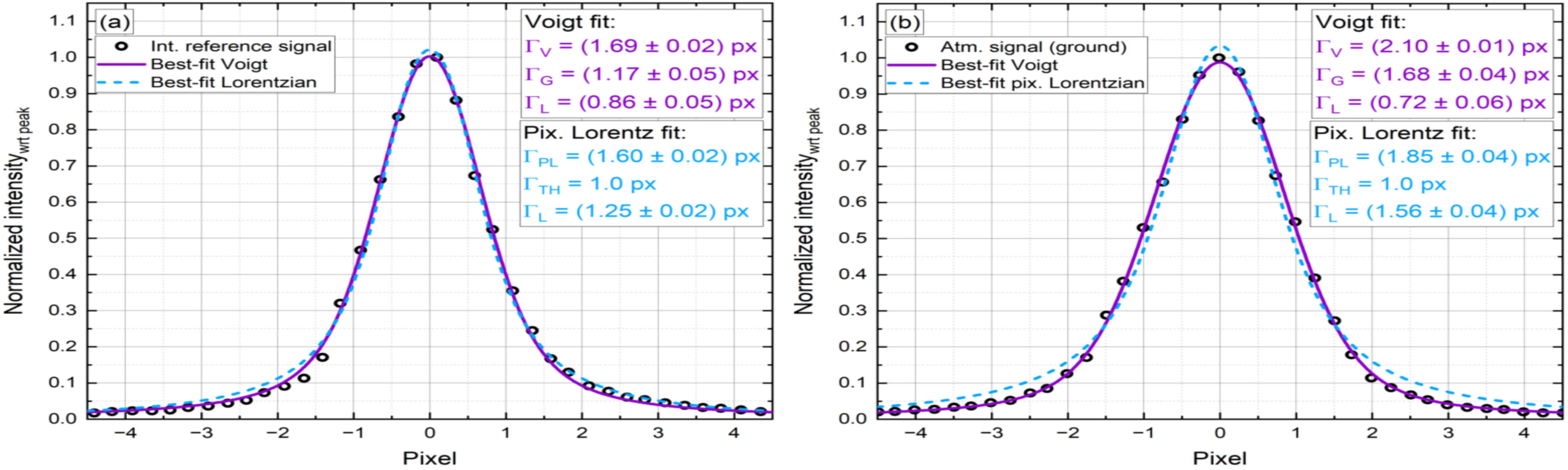
Setup and performance of



Benjamin Witschas, DLR, Laser Congress 2025, 20. Oct. 2025

Fizeau spectral performance

DLR



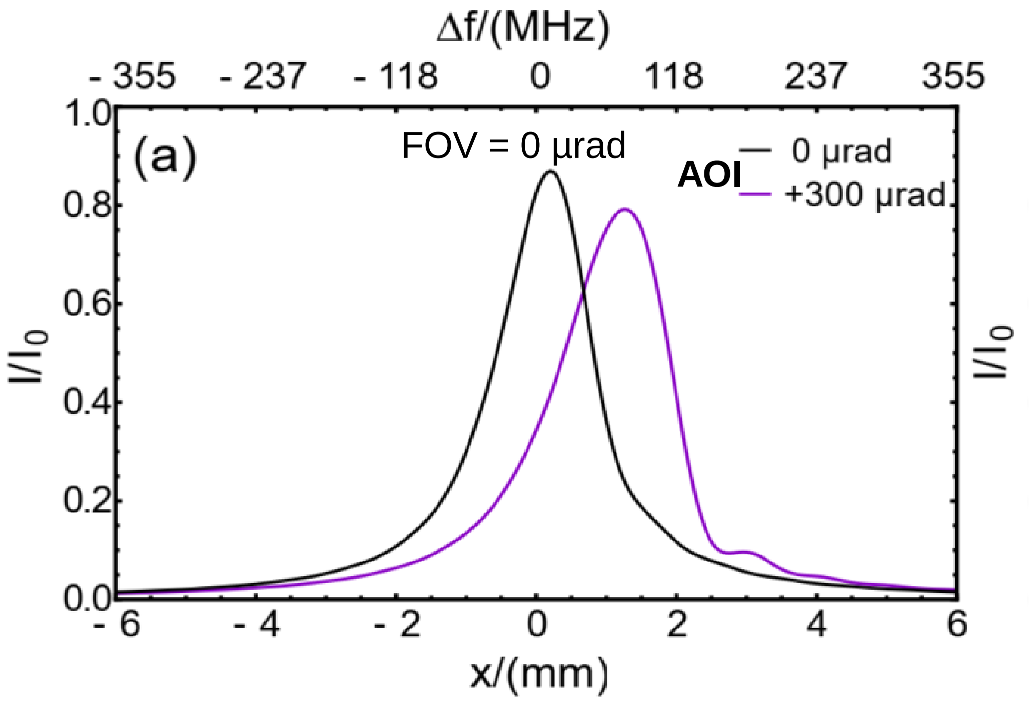
(1) Both, INT and ATM are **not Lorentzian shaped** but well described by a Voigt profile (*G***L*)

(2) The FWHM of the ATM path is significantly larger than expected (Laser, Interferometer, Detector); about **210 MHz** (+23%)

- Witschas et al., Appl. Opt., 2023: “Verification of different Fizeau fringe analysis algorithms based on airborne wind lidar data…”.
- Wang et al., AMT, 2024: “Evaluation of Aeolus feature mask and particle extinction coefficient profile products using CALIPSO data”.
- Vaughan et al., AMTD, 2024: “Spectral performance analysis of the Fizeau interferometer onboard ESA’s Aeolus wind lidar satellite”.

Wave optic modelling of Fizeau fringes

- A rigorous **wave optic based** model of the Fizeau interferometer was developed by Vaughan and Ridley leading to investigate the impact of existing **polishing rings** and **speckle effects**.
- This wave optic model was adapted and used to investigate the impact of the angle of incidence (AOI) and field of view (FOV).



A **FOV of 500 µrad** with **AOI of 300 µrad** can explain both, the actual fringe width and the Voigt shape.
Similar enhanced AOIs were derived from the Fabry-Perot int. data (not shown, Witschas et al., 2022).

Summary

- 1st European lidar and 1st wind lidar in space in operation for 4 years and 10 months (from Aug 2018 until July 2023); lifetime objective (3.5 years) achieved and demonstration of wind lidar technology in space.
- 1st successful demonstration of operation of a UV laser in space with stable performance of both lasers (end of life of Aeolus was not determined by the instrument, but by the satellite fuel and solar activity).
- 1st demonstration of positive impact of wind profiles for numerical weather prediction with even operational use for daily forecasts since January 2020: ECMWF, DWD, Météo-France, UK Met Office and NCMRWF.
- Paved the way for follow-on lidar missions and laser applications in space.

Outlook
Aeolus2: An Aeolus successor mission, but more than a copy

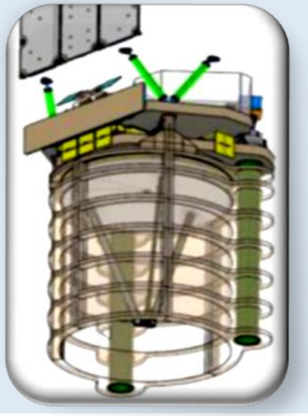
Due to the success of Aeolus and the resulting socioeconomic benefits, **a follow-up mission was selected at the 2022** ESA Ministerial Council meeting.

Aeolus-2 (2034)

- Joint **ESA/EUMETSAT** mission
- **2 satellites**, >5 years lifetime, with temporal overlap
- Aeolus-2 will have a similar design but with significant modifications → Aeolus next generation

Planned design changes

- **Bi-static configuration** → risk reduction regarding laser-induced contamination and less polarization-sensitive optics (potential sources of signal loss)
- **Significantly heavier** (997 kg instead of 455 kg) due to two independent transmission paths
- **Co-alignment loop** and possibly **new spectrometers** required
- **Pressurized laser housing, new detectors**



→ Detailed investigations needed and performed by industry and at DLR by using on an airborne demonstrator instrument → next talk by C. Lemmerz

THANK YOU FOR YOUR ATTENTION!