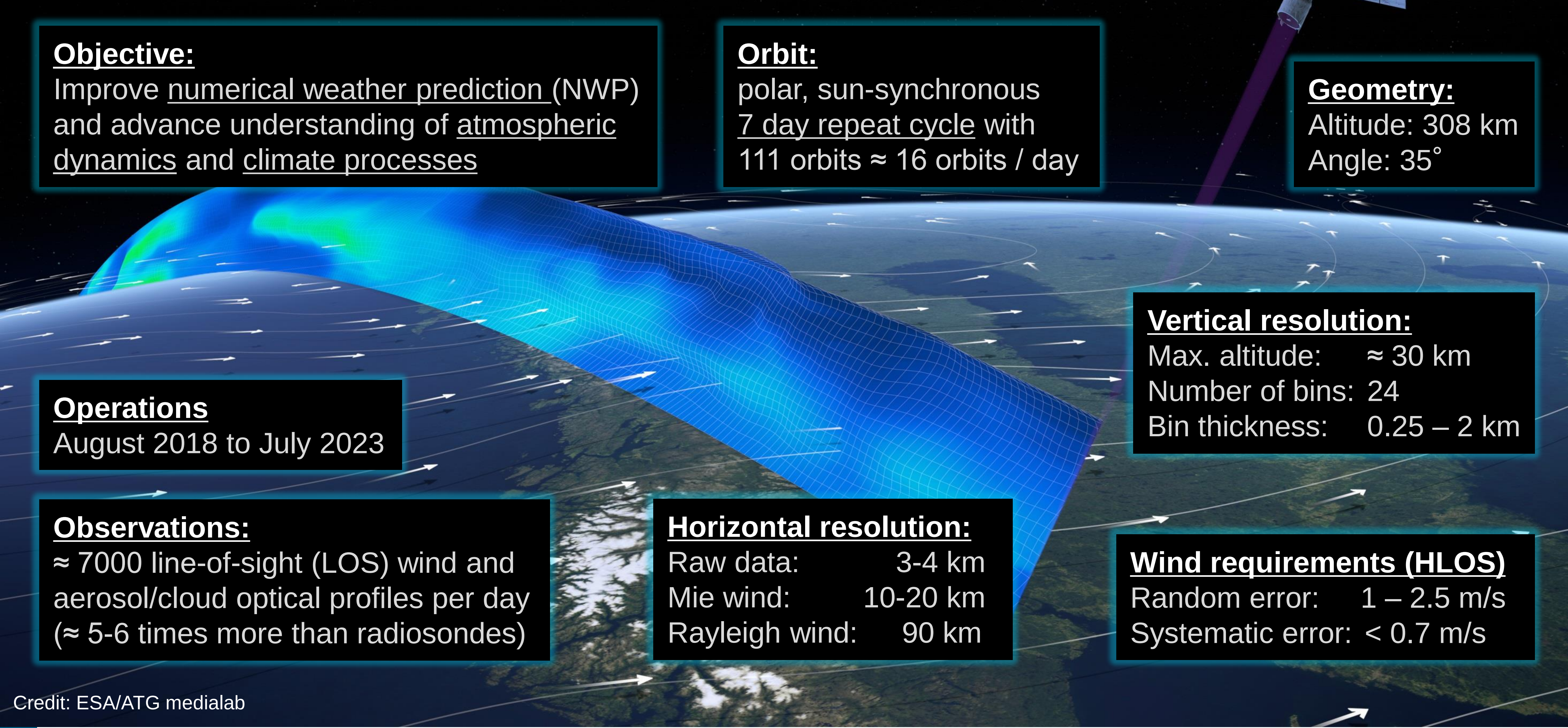
M. Rennie,	09:30: Aeolus impact on NWP
M. Porciani,	10:10: How Aeolus shaped Aeolus-2
B. Boyes,	10:30: Aeolus-2/EPS Aeolus Overview
T. Flament,	10:50: Scientific Activities regarding EPS-Aeolus
C. Lemmerz,	13:50: Aeolus Airborne Validation

The Aeolus Data Innovation and Science Cluster (DISC): Aeolus mission support from Launch to end-of-life and beyond

B. Witschas (DLR), O. Reitebuch (DLR) and Tommaso Parrinello (ESA) on behalf of the Aeolus DISC

Workshop on Space-based Measurements of 3-Dimensional Winds
19 to 20 February 2025,NOAA Center for Weather and Climate Prediction (NCWCP), College Park, MD

ESA's Aeolus wind lidar mission (2018 - 2023)



Objective:
Improve numerical weather prediction (NWP) and advance understanding of atmospheric dynamics and climate processes

Orbit:
polar, sun-synchronous
7 day repeat cycle with
111 orbits ≈ 16 orbits / day

Geometry:
Altitude: 308 km
Angle: 35°

Vertical resolution:
Max. altitude: ≈ 30 km
Number of bins: 24
Bin thickness: 0.25 – 2 km

Operations
August 2018 to July 2023

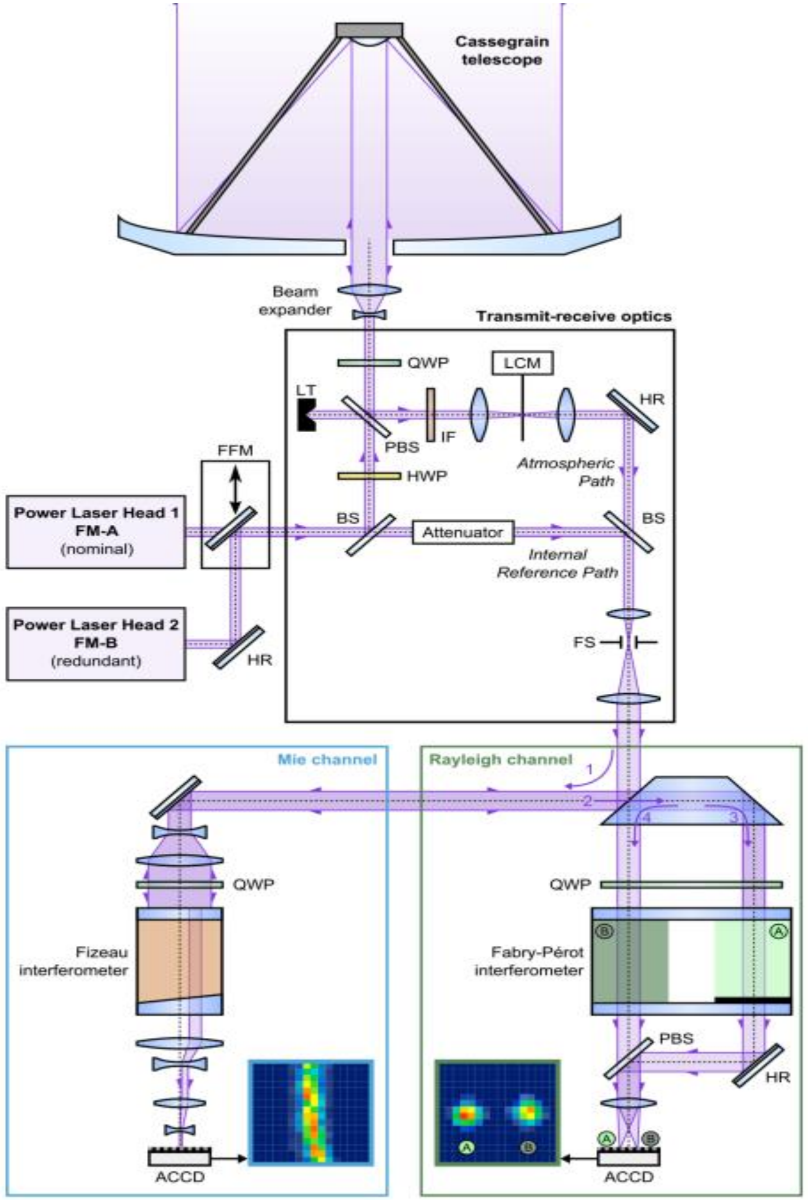
Observations:
≈ 7000 line-of-sight (LOS) wind and aerosol/cloud optical profiles per day
(≈ 5-6 times more than radiosondes)

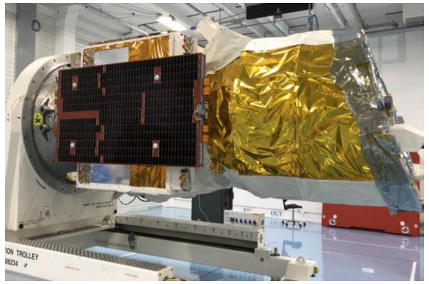
Horizontal resolution:
Raw data: 3-4 km
Mie wind: 10-20 km
Rayleigh wind: 90 km

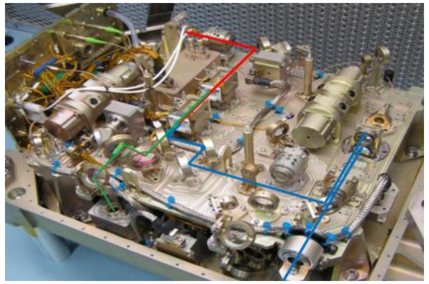
Wind requirements (HLOS)
Random error: 1 – 2.5 m/s
Systematic error: < 0.7 m/s

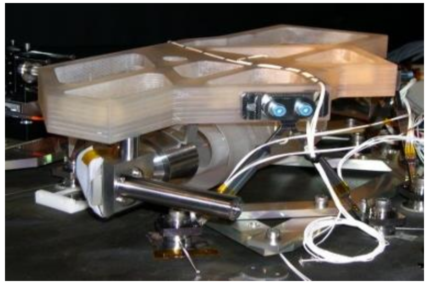
Credit: ESA/ATG medialab

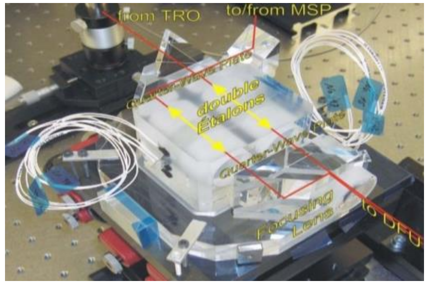
The ALADIN setup – a technological challenge











- **First European lidar** in space after 20 years of development challenges
- **First wind lidar in space**
- **First high-power, ultraviolet (UV) laser** in space (@ 354.8 nm) with stringent requirements on frequency stability (< 10 MHz rms)
- **Challenging direct-detection** approach, due to need for winds from broad-bandwidth molecular Rayleigh backscatter up to altitudes of 20-30 km

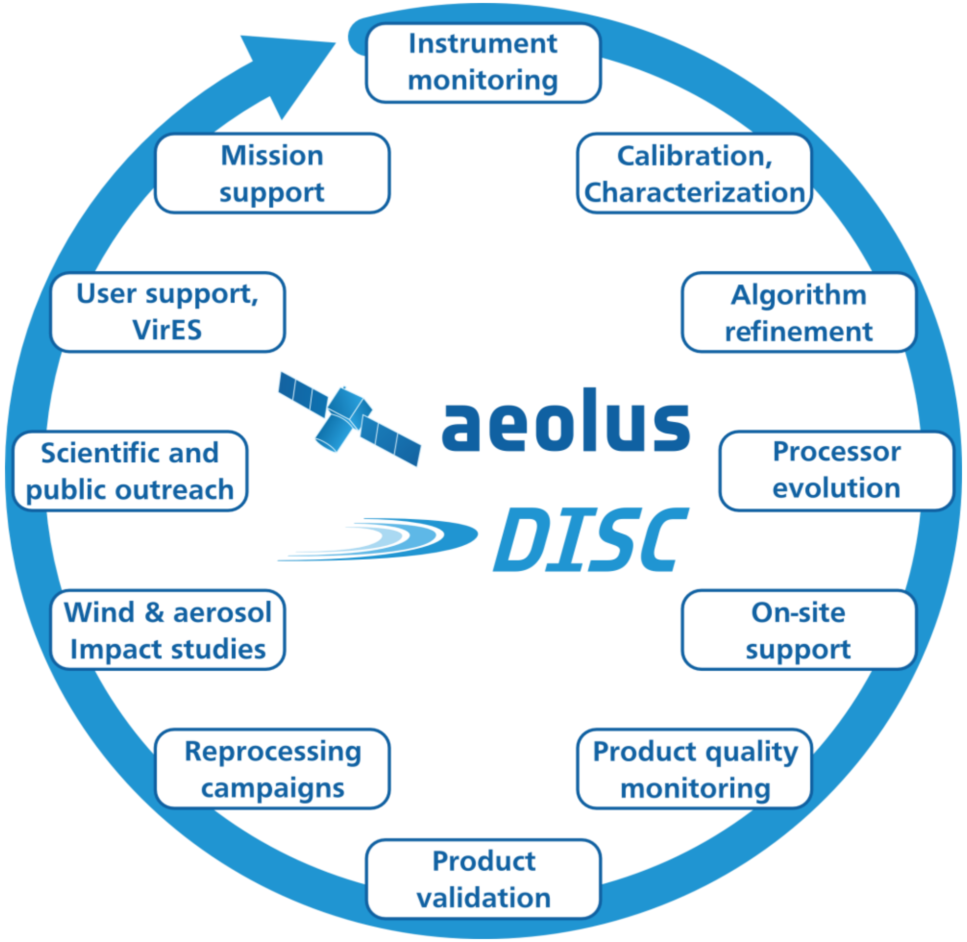
Sketch from Lux et al., 2021, AMT; credits of photographs: Airbus DS

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.

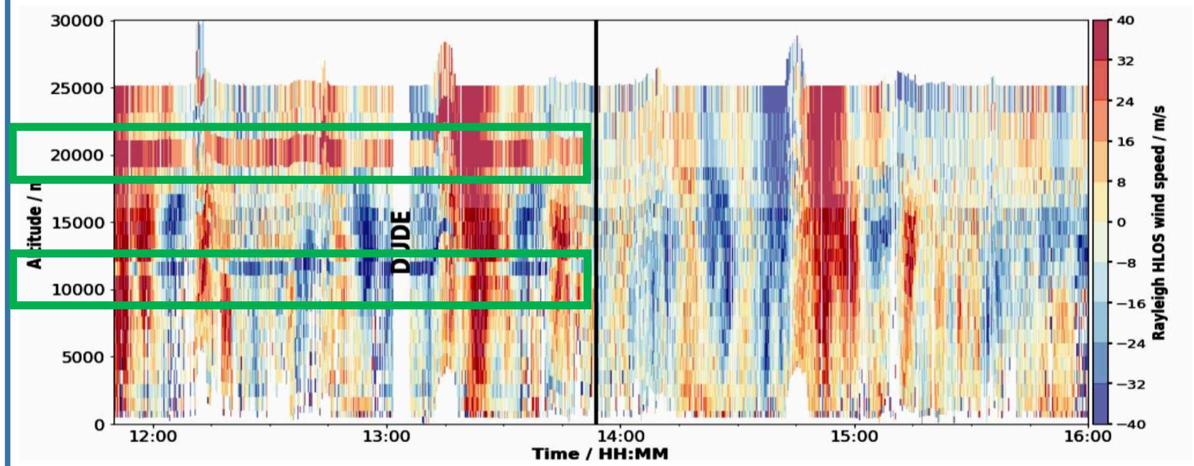
- DISC was kicked-off 2019 (until 2028) **with teams cooperating since 2003** and funded by ESA
- **14 international partners** with **≈40 scientists** and engineers coordinated by DLR
- **Broad range of experts** and **strong links to all ESA entities**, **space industry** and **science community**

DISC Meeting at ESRIN in Frascati March 2024



Investigating and correcting "unexpected" bias sources
Hot pixels and telescope temperature variations

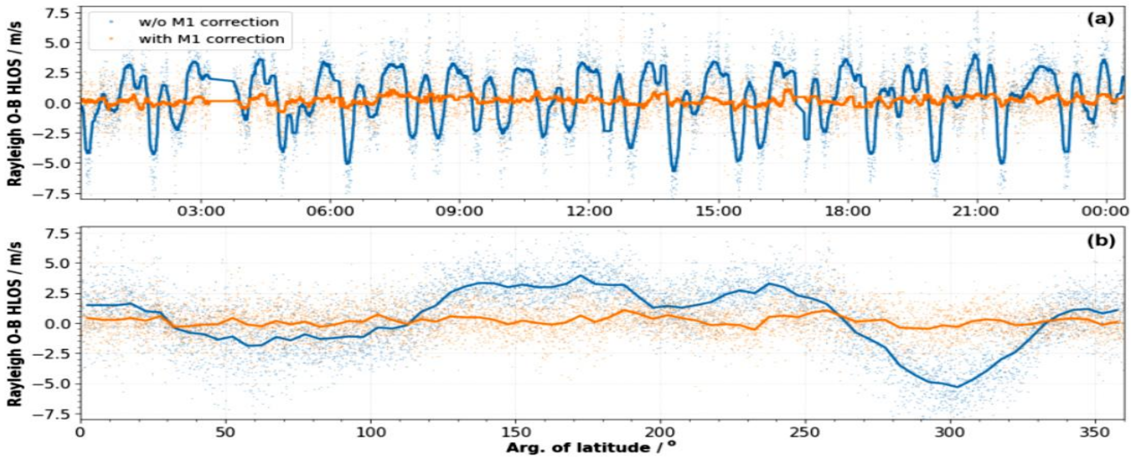
Hot pixels



Enhanced dark current rates on hot pixels of the CCD detector lead to **biases of up to several m/s**.

→ Corrected with special instrument operation mode **DUDE** (Down Under Dark Experiment, 4 to 8 per day) and on-ground correction in L1B processor since 14 June 2019

Telescope temperature variations

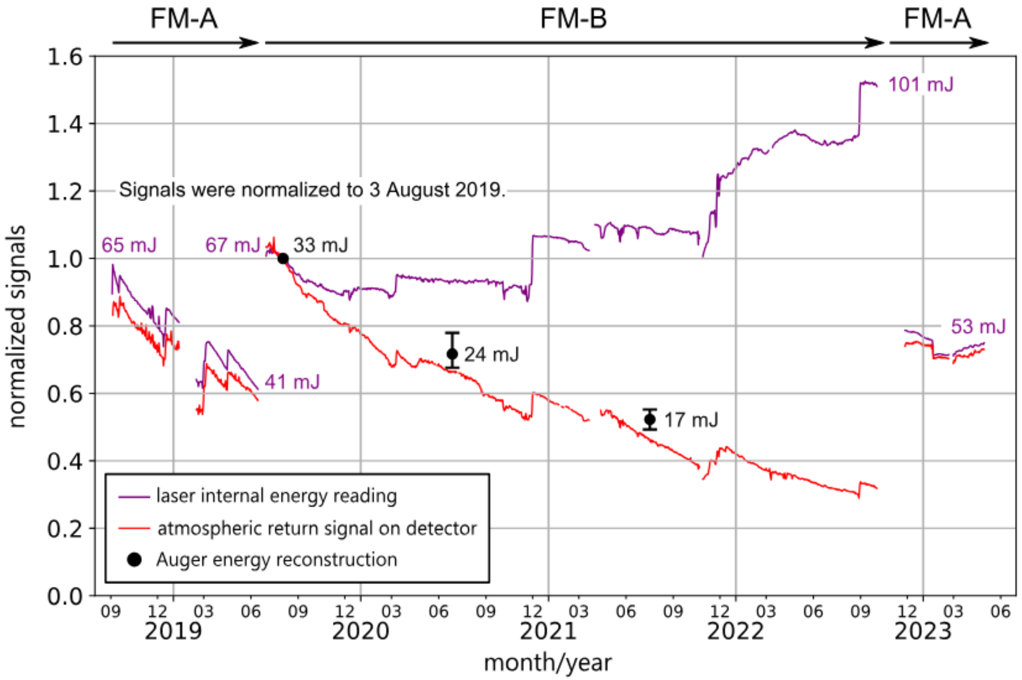


M1 telescope mirror T-variations (mean + gradient along the mirror) lead to orbit-dependent **biases of several m/s** (for both Mie and Rayleigh).

→ Corrected using correlation between M1 temperatures and ECMWF model bias (O-B) every 12/24h; implemented since 20 April 2020 (<u>using ground-return correction works with 10% lower performance</u>).

- Weiler et al., AMT, 2021: "Characterization of dark current signal measurements of the ACCDs used on board the Aeolus satellite".
- Weiler et al., AMT, 2021: "Correction of wind bias for the lidar on board Aeolus using telescope temperatures".

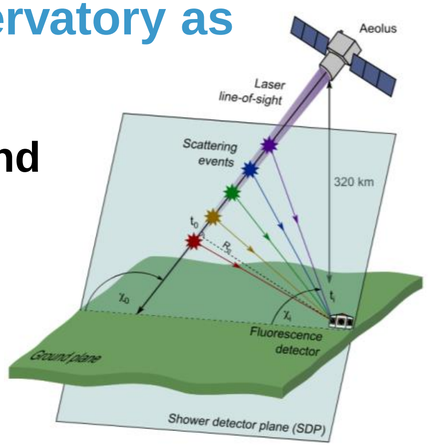
Laser energy performance characterization
"Cosmology meets Earth Observation"



Cosmic rays are detected by secondary UV air showers in the atmosphere at the Pierre Auger Observatory (Argentina)

→ First measurements of a space-borne UV laser beam by an Earth-based cosmic particle observatory as support of the Aeolus mission:

- Accurate determination of the laser beam **ground track** per shot (within 200 m)
- Independent measurement of the emitted **laser energy at the output of the telescope**
- Same approach is used now for **EarthCARE**



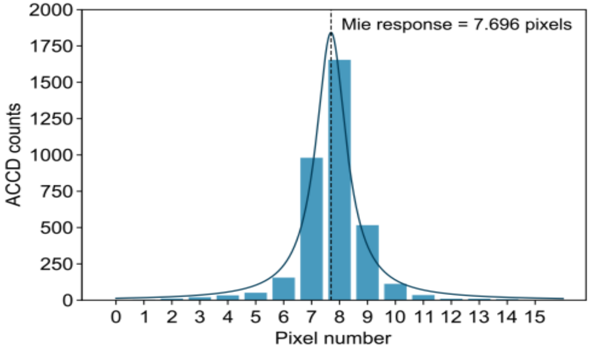
- The reconstructed energies from the Pierre Auger Observatory allowed for **an independent assessment of the ALADIN laser performance** between 2019 and 2021 (FM-B laser).
- The ATM signal (Ray) **decreased by 70%** within 3 years → loss on the emit-path (between laser & telescope) on optics unique to FM-B path (LIC/LID behind the laser as most probable causes).
- **UV laser energy was incrementally increased to >100 mJ** to counteract the signal loss.*

- Pierre Auger Collaboration, et al., Optica, 2024: "Ground observations of a space laser for the assessment of its in-orbit performance".
- Lux et al., Appl. Opt., 2024: "Performance of the ultraviolet laser transmitter during ESA's Doppler wind lidar mission Aeolus".

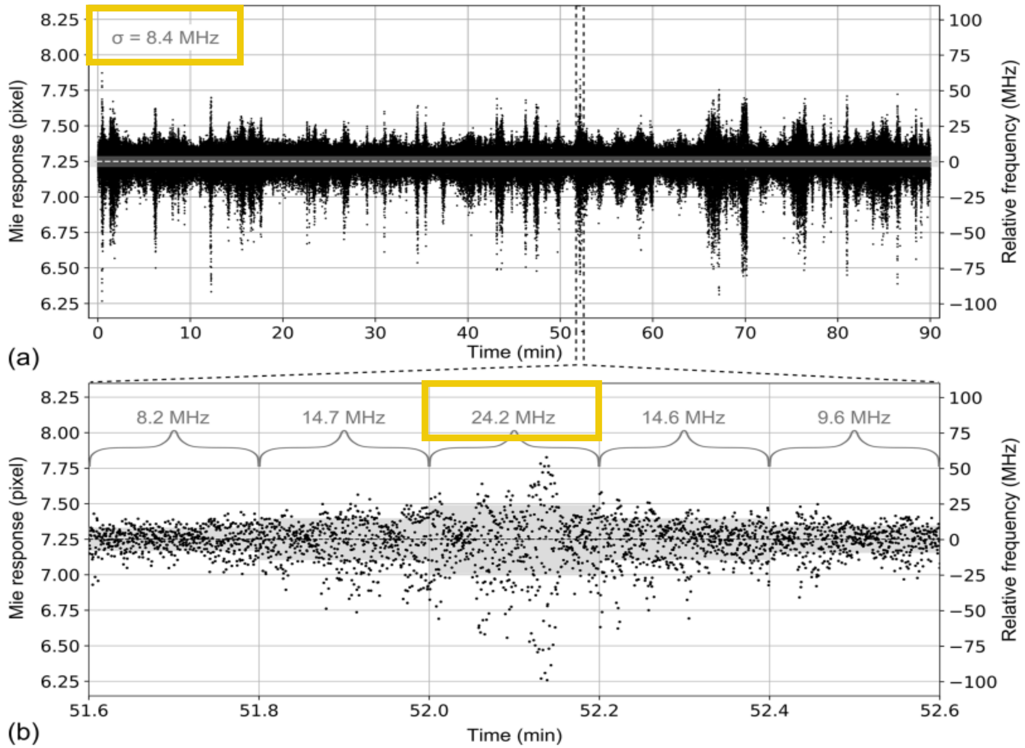
Laser frequency stability characterization

ALADIN as wavemeter

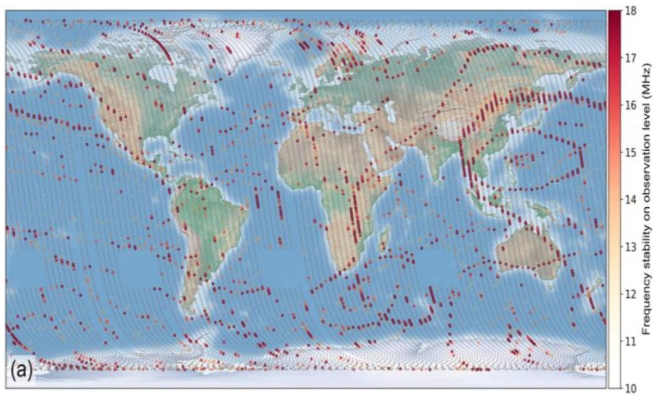
The internal reference signal together with the Fizeau interferometer are used as a wavemeter
→ **frequency stability from shot-to-shot**



Laser frequency fluctuations along one orbit



Wind observations with enhanced frequency noise



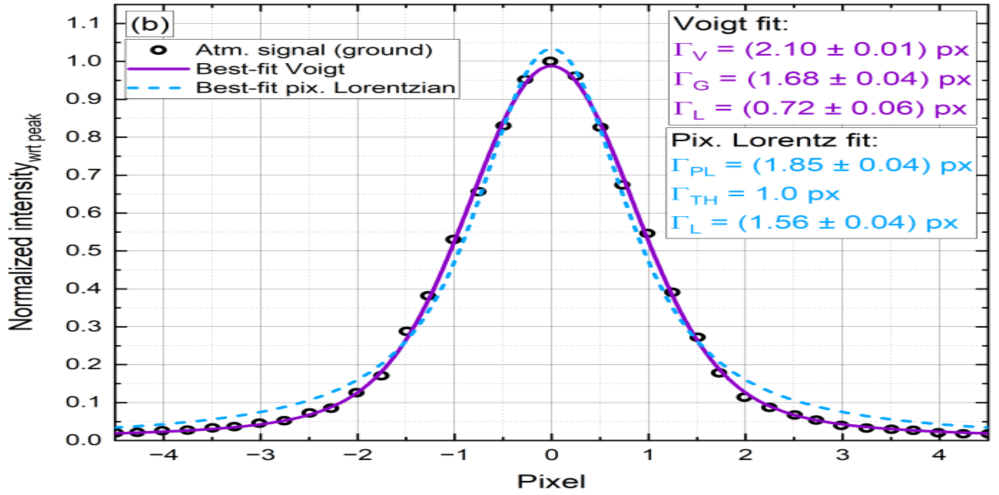
- Dependency on geolocation
  → regions with critical rotation speeds of the satellite's reaction wheels
  → micro-vibrations

- 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".

Instrument characterization and algorithm optimization
Fizeau fringe analysis and spectral performance

Fizeau fringe analysis & algorithms



- For a precise fringe measurement and characterization, a method for correcting the illumination fct. was developed (fringe imaging).
- Fringe follows a **Voigt** spectral shape (instead of Lorentzian) with a larger **width of ~210 MHz** **(explained by laser pulse profile and off-axis illumination with a few 100 µrad)**

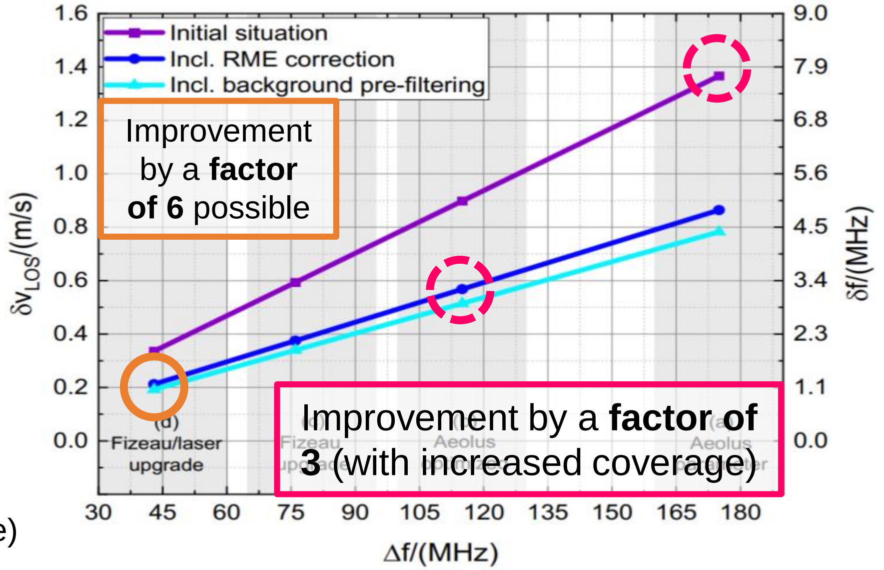
Fizeau spectral performance

The quantum limited accuracy ***δf* for the Mie-channel** is given by the **Cramer-Rao lower bound** (approx. for negligible background → only shot-noise of the signal):

$$\delta f = \frac{C_{\mathrm{CR}} \cdot \Delta f}{\langle N_S \rangle^{1/2}},$$

$$\mathrm{SNR} = \frac{\langle N_S \rangle}{\langle N_S \rangle^{1/2}} = \langle N_S \rangle^{1/2}$$

- **Δ*f* is the FWHM** before detection
- **⟨N_S⟩ the mean number of electron-counts**
- **C_{CR} is a constant** ~ 1 (shape)

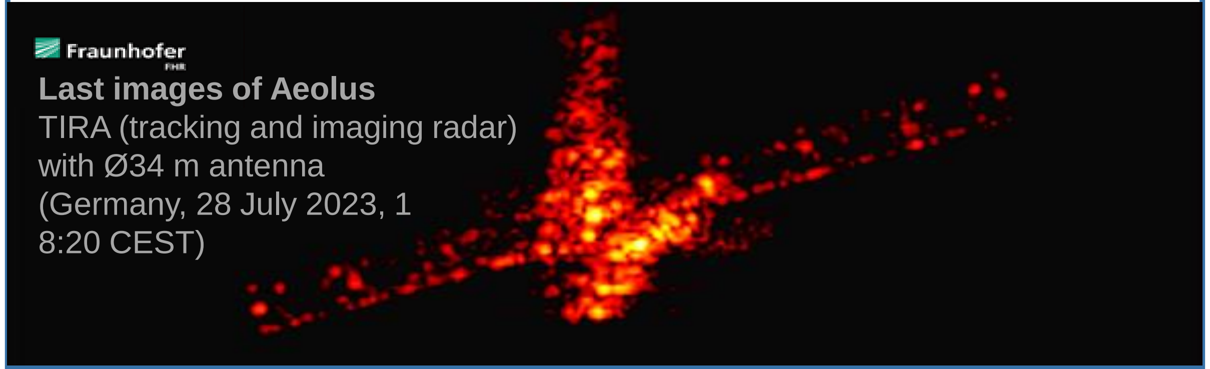


- A tool for calculating the quantum limited accuracy for the Aeolus Mie channel was developed, showing the **possibility of improvements by a factor of 3** to 6.

- 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”.

End of life and reprocessing
Valuable work and the end and after the mission

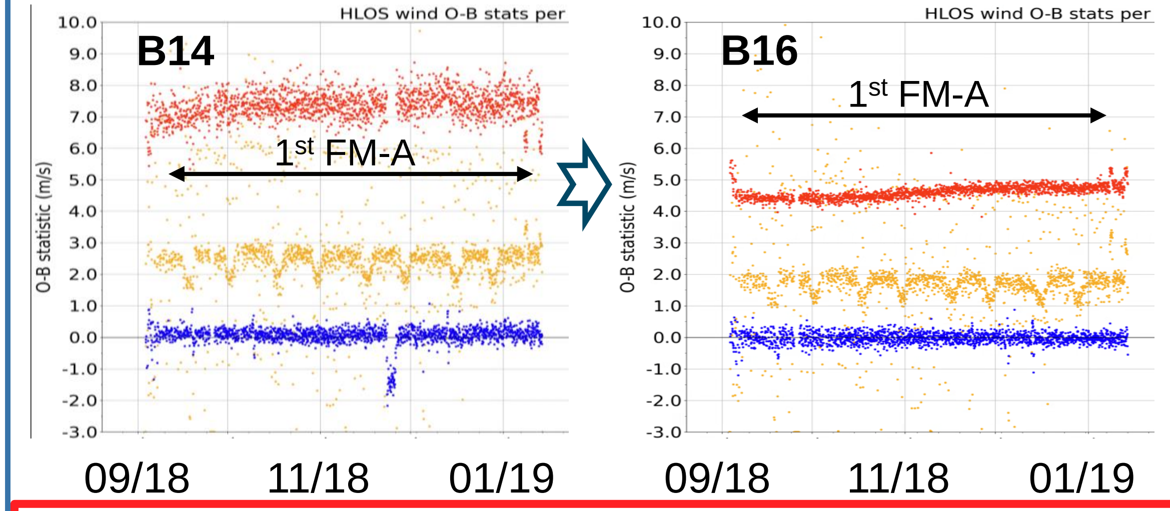
End-of-life tests – a two-months test phase with Aeolus as space lidar lab



- Confirmation that **hot pixels** are radiation-induced (T-dependency obeys Arrhenius law), not clock-induced
- Improving the **laser frequency stability** by ~factor of 2 due to an improved master oscillator cavity control setting, better compensating micro-vibrations
- Operating UV laser with a **record energy of 182 mJ**
- Increasing the **internal reference signal stability** by optimizing the laser chopper settings
- … and many more

Data reprocessing (currently B16)

Rayleigh-clear winds



Improvement of Ray.-clear random error by 20% to 30%

- Improving calibrations and corrections (hot pixel)
- Improving the estimated error assessment which results in better quality control
- Updating algorithms (e.g., Voigt instead of Lorentzian for Mie channel data)
- …and many more

Summary
The 7 major challenges and achievements of Aeolus

- 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.
- Demonstration of high-spectral resolution lidar for retrieval of aerosol extinction in orbit → demonstrated potential also for enhanced aerosol capabilities for EarthCARE with depolarization channel.
- 1st ESA Mission with an assisted re-entry on 28 July 2023, although not being designed for it.
- Aeolus succeeded in becoming an operational, meteorological follow-on program with the decision on ESA´s Ministerial Meeting in November 2022, socio-economic study from EUMETSAT indicates benefit-cost ratio for EPS-Aeolus of factor 20 and factor 33 adding EPS-Sterna.
- Aeolus paved the way for the future European lidar missions (EarthCARE, Merlin) and EPS-Aeolus wrt. **technology, framework and cooperation** of ESA, industry, DISC, NWP, Cal/Val, science community.

Backup

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- Lux, O., Reichert, R., Lemmerz, C., Masoumzadeh, N., Wernham, D., Candra Krisna, T., Marchais, D., Bell, R., Parrinello, T., and Reitebuch, O.: CCD detector performance of the space-borne Doppler wind lidar ALADIN during the Aeolus mission, Appl. Opt., 63, 6754–6775, 2024.
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- Weiler, F., Rennie, M., Kanitz, T., Isaksen, L., Checa, E., de Kloe, J., Okunde, N., and Reitebuch, O.: Correction of wind bias for the lidar on board Aeolus using telescope temperatures, Atmos. Meas. Tech., 14, 7167–7185, https://doi.org/10.5194/amt-14-7167-2021, 2021b.
- Witschas, B., Lemmerz, C., Lux, O., Marksteiner, U., Reitebuch, O., Weiler, F., Fabre, F., Dabas, A., Flament, T., Huber, D., and Vaughan, M.: Spectral performance analysis of the Aeolus Fabry–Pérot and Fizeau interferometers during the first years of operation, AMT, 15, 1465–1489, https://doi.org/10.5194/amt-15-1465-2022.
- Witschas, B., Vaughan, M., Lux, O., Lemmerz, C., Nikolaus, I., and Reitebuch, O.: Verification of different Fizeau fringe analysis algorithms based on airborne wind lidar data in support of ESA's Aeolus mission, Appl. Opt., 62, 7917–7930, https://doi.org/10.1364/AO.502955, 2023b.

Major Lessons Learnt

- **Winds were / are / and will be important for improving weather forecasts** => Aeolus-2 / EPS-Aeolus.
- **Doppler lidar technology as pioneered on Aeolus proved to provide wind profiles** from ground up to 25 km, but significant improvements are needed to fulfill NWP requirements in the 2030s timeframe:
  - Higher vertical range up to 30 km and capability up to 40 km (=> detector)
  - Higher vertical and horizontal resolution (SNR, detector)
  - meeting Aeolus random error requirements (2.5 m/s HLOS)

  $\Rightarrow$ Factor 4 improvements in signal levels needed compared to Aeolus in-orbit performance.
- **UV laser operated in space**, despite LIC/LID => O_2 cleaning (ALADIN) or pressurized laser housing (ATLID); higher laser energy and higher efficiency needed
- **SiC telescope with Ø1.5 m: thermal-optical stability** along the orbit was not sufficient, although thermally stabilized:=> de-focus, signal loss, and wind bias => trade-off mass/thermal inertia; thermal-control.
- **On-ground end-to-end performance verification in TVac was (too) limited** and missed important issue with radiometric budget: initial signal loss of Aeolus.
- **CCD-detector technology**: issue with radiation-induced hot-pixels; missed with standard radiation test procedures on-ground.
- **Airborne demonstrator** for the space-borne instrument was a key asset for prep. and Cal/Val.