THE WAY TO A PERFORMANCE SIMULATOR FOR EPS-AEOLUS

Uwe Marksteiner[1)], *Stefanie Knobloch[1)], Benjamin Witschas[1)], Oliver Reitebuch[1)], Markus Meringer[2)], Dorit Huber[3)], Katja Reissig[4)]*

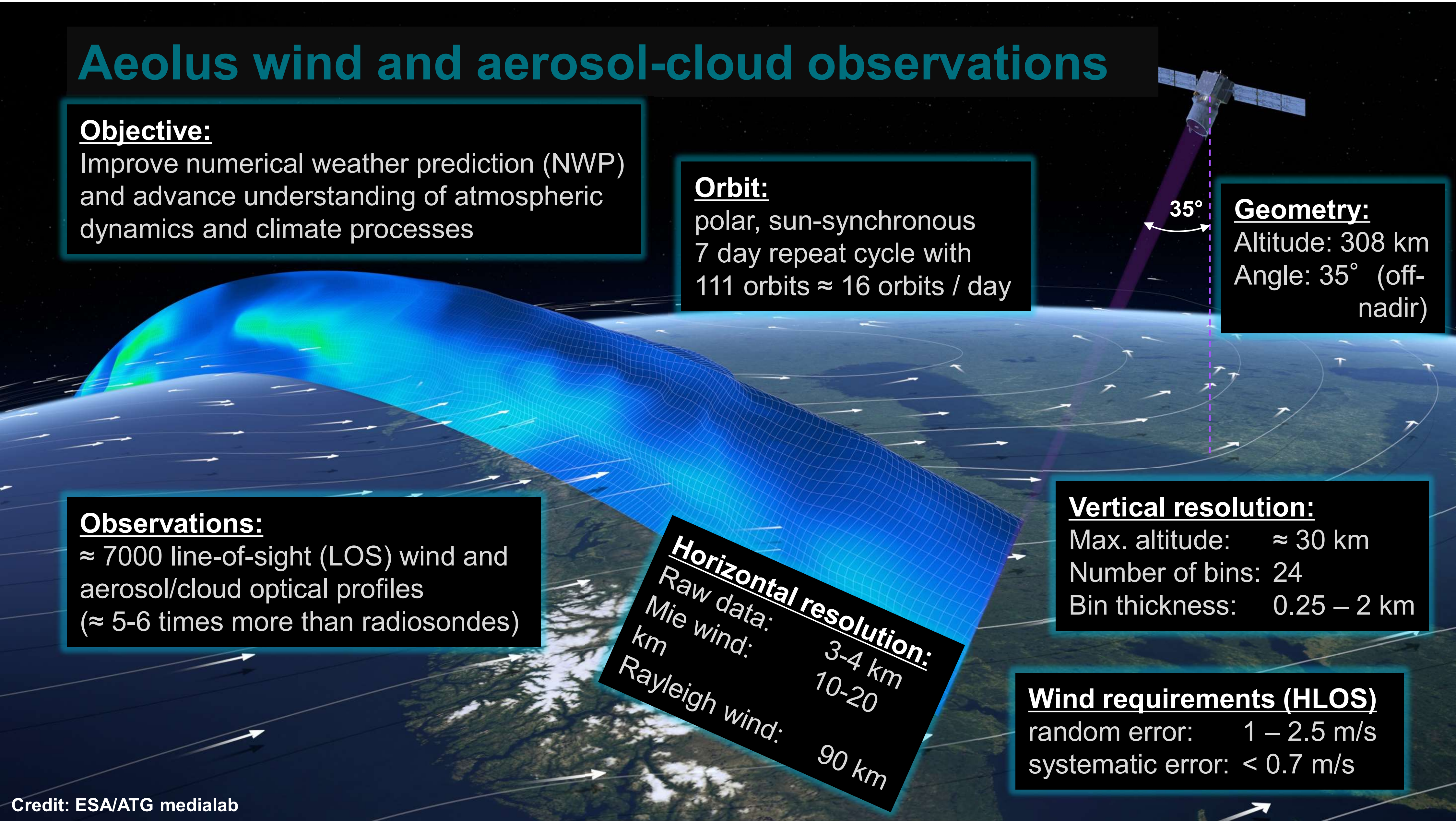
Theme: *03. Towards new operational programmes and preparedness studies*

Session Details: *3-H EPS-Aeolus / Thursday, Oct. 3, 2024*

Presentation Time: *11:45 AM – 12:00 PM*

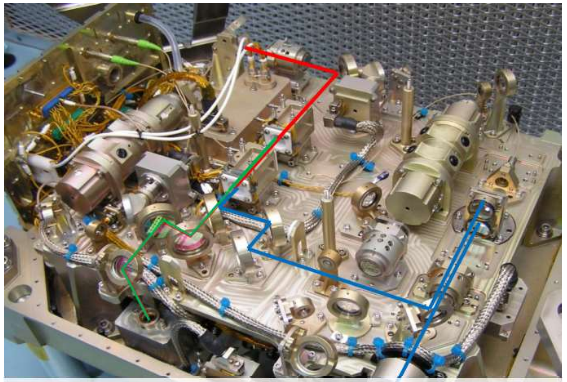
Paper Number: *109*

[1)] Institute of Atmospheric Physics, German Aerospace Center DLR, Oberpfaffenhofen 82234, Germany
[2)] Remote Sensing Technology Institute, German Aerospace Center DLR, Oberpfaffenhofen 82234, Germany
[3)] DoRIT on Research Information Technology, Fürstenfeldbruck 82256, Germany
[4)] IB Reissig, 86923 Finning, Germany

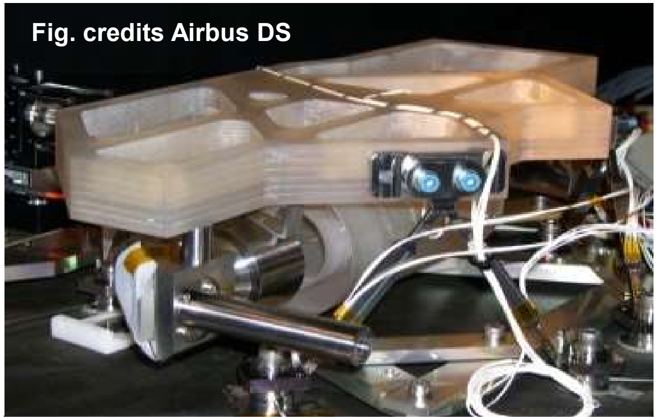

Aeolus wind and aerosol-cloud observations
Objective:
Improve numerical weather prediction (NWP) and advance understanding of atmospheric dynamics and climate processes
Orbit:
polar, sun-synchronous
7 day repeat cycle with
111 orbits ≈ 16 orbits / day
35°
Geometry:
Altitude: 308 km
Angle: 35° (off-nadir)
Observations:
≈ 7000 line-of-sight (LOS) wind and aerosol/cloud optical profiles
(≈ 5-6 times more than radiosondes)
Horizontal resolution:
Raw data: 3-4 km
Mie wind: 10-20 km
Rayleigh wind: 90 km
Vertical resolution:
Max. altitude: ≈ 30 km
Number of bins: 24
Bin thickness: 0.25 – 2 km
Wind requirements (HLOS)
random error: 1 – 2.5 m/s
systematic error: < 0.7 m/s
Credit: ESA/ATG medialab

ALADIN – a technological challenge

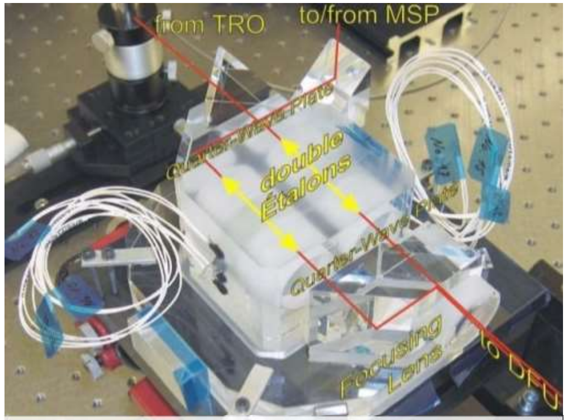
Aeolus satellite



ALADIN laser transmitter



Mie spectrometer



Rayleigh spectrometer

- **Launch** 22 August 2018, **nominal lifetime** of 3.5 years **exceeded** with operation until 5 July 2023, and **assisted re-entry** on 28 July 2023
- **First European lidar in space** after 20 years of development challenges and **first wind lidar in space**
- **First high-power, ultraviolet (UV) laser** in space (@ 354.8 nm) with stringent requirements on frequency stability (<7 MHz rms)
- **Doppler wind lidar principle** – straightforward but incredibly small wavelength shift
- **Challenging direct-detection** approach, due to need for winds from broad-bandwidth molecular Rayleigh backscatter up to lower stratosphere

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

relative Doppler shift: $\Delta f = 2 f_0 \frac{v_{\mathrm{LOS}}}{c}$

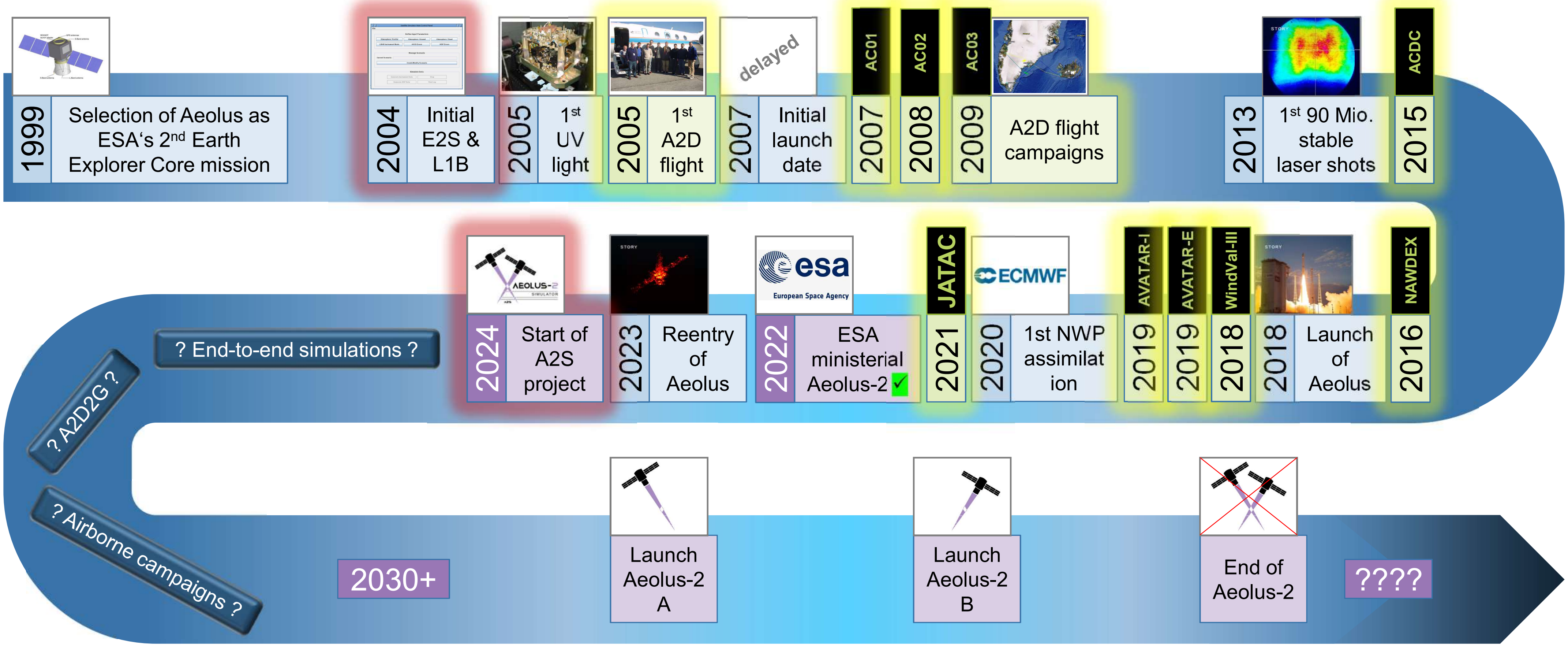
→ 1 m/s (LOS) **~ 5.64 MHz ~ 2.37 fm**

Reitebuch *et al. (2009) JAOT /* ***Reitebuch*** *(2012) Springer /* ***Reitebuch and Hardesty*** *(2022) Springer*

Aeolus – History and future

… accompanied by the End-to-End Simulator (E2S) & the Aeolus Airborne Demonstrator (A2D)

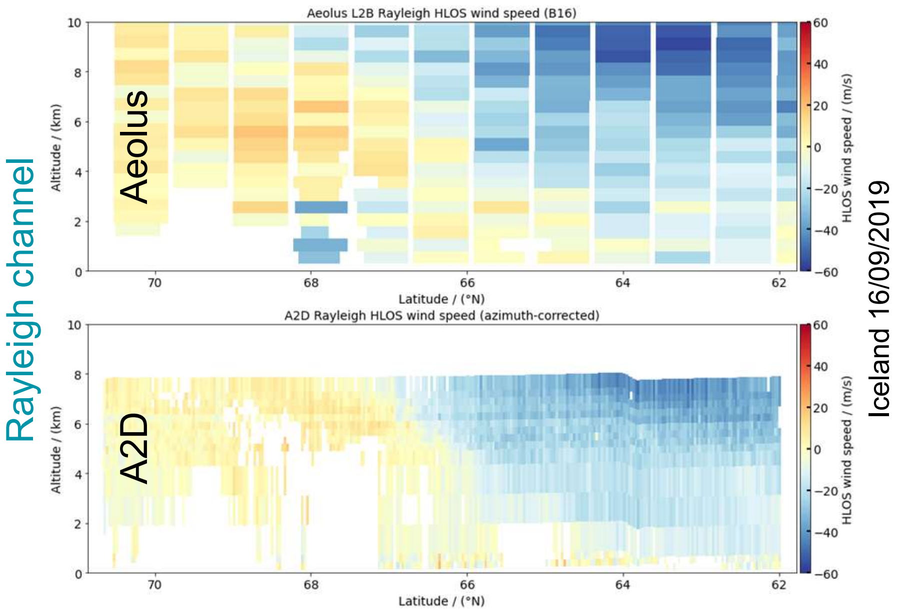
→ Pre-launch: **> 100 recommendations** derived for Aeolus instrument alignment, operation, retrieval algorithms and CalVal

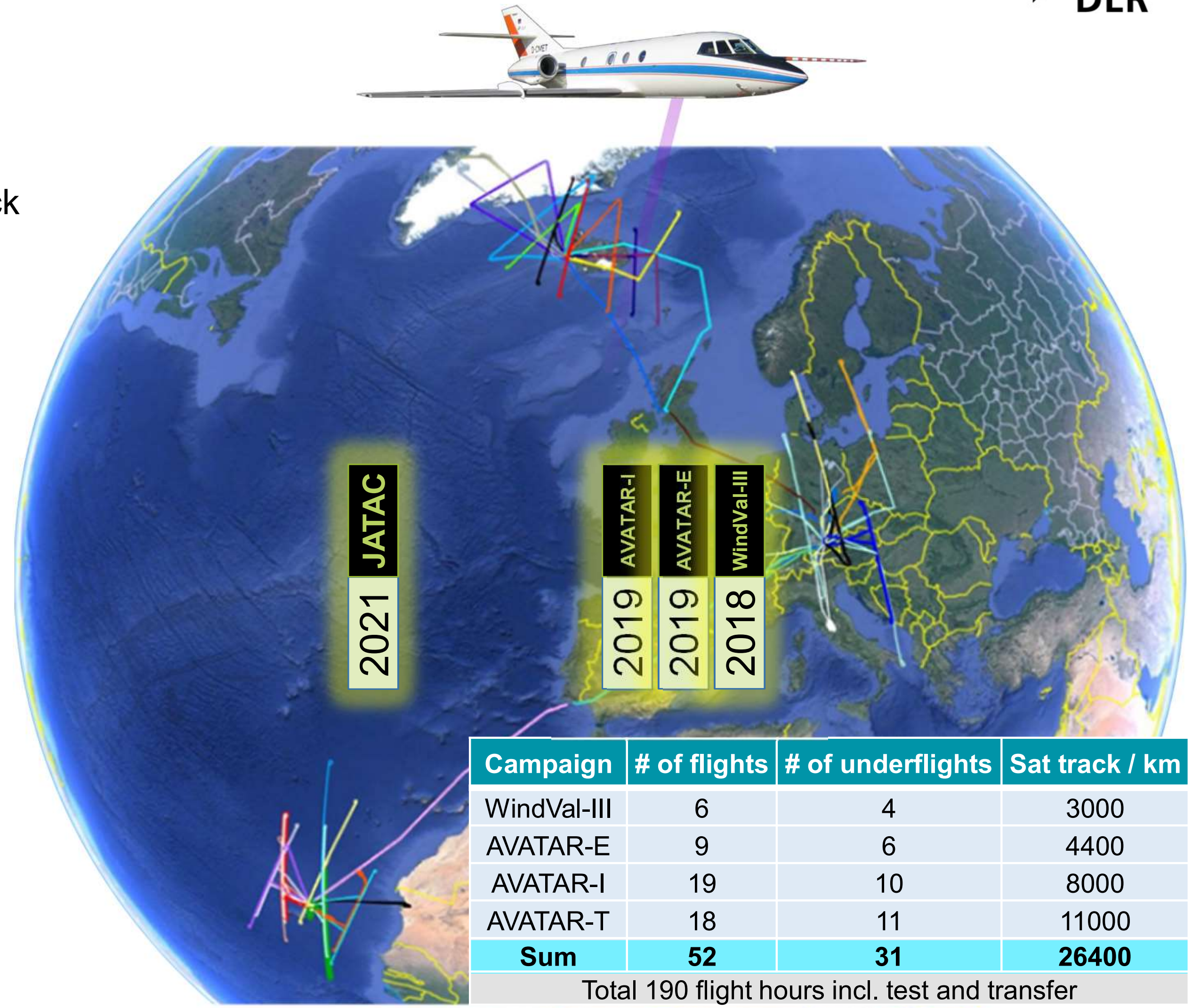


Aeolus Airborne Validation Campaigns After Launch

- **4 airborne campaigns** employing the A2D
- **52 flights** with **26400 km** along the Aeolus track

→ **high resolution** and **high quality** data



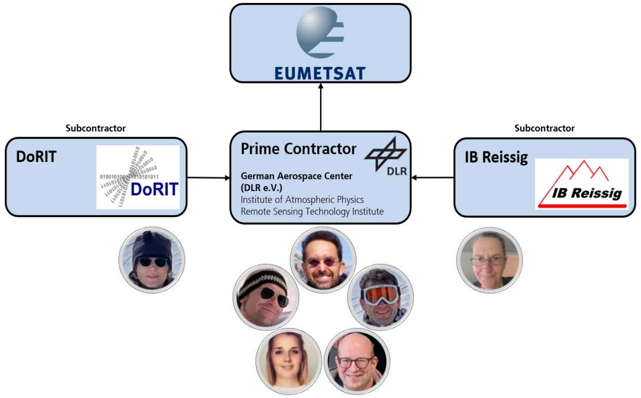


Campaign	# of flights	# of underflights	Sat track / km
WindVal-III	6	4	3000
AVATAR-E	9	6	4400
AVATAR-I	19	10	8000
AVATAR-T	18	11	11000
Sum	**52**	**31**	**26400**
Total 190 flight hours incl. test and transfer			

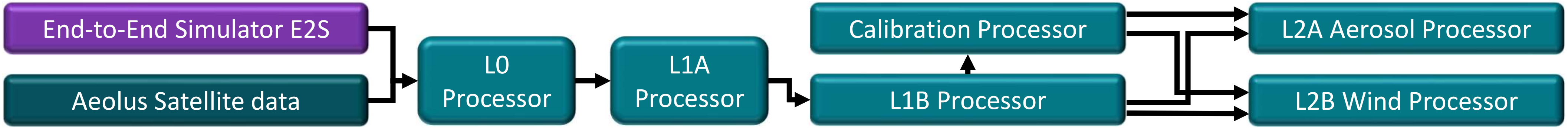
***Lux** et al. (2020 & 2022), AMT; **Witschas** et al. (2020 & 2022), AMT*

The Aeolus-2 Simulator (A2S) Study

- The **purpose** of this study (Jan. 2024 – Apr. 2025):
  - **Re-configure** the Aeolus End-to-End Simulator (**E2S**)
  - **Assess the radiometric performance** of the Aeolus Rayleigh channel (Mie channel more complicated) by comparing simulated and measured signals
  - Run **simulations** representative of the planned **EPS-Aeolus** mission performance (without updating the E2S software code).
  - Investigation of a Dual **Michelson** interferometer (DMI) to assess the influence of **Mie contamination on the Rayleigh** channel + **accuracy** of the correction



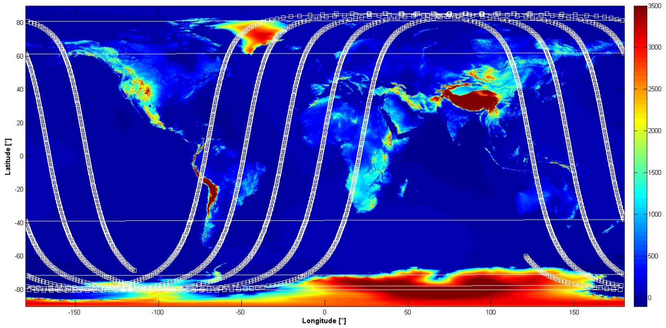
- The great **potential** of the Aeolus End-to-End Simulator (**E2S**):
  - The E2S was **used extensively** in combination with the Aeolus L1B, L2A and L2B processors before launch for performance simulations, algorithm sensitivity studies and functional testing **over 15 years**.
  - Significant work was invested in the E2S to simulate atmosphere and the ALADIN instrument **close to reality** before launch
  - After launch, the E2S was used for **estimation** of initial signal loss (DLR) and the **investigation** of noise in the L2A retrievals (Météo France, ESA-ESTEC) and is now used in the functional **testing** during the processor delivery (DoRIT, KNMI)
  - Functional **updates** of the E2S (compatible with L1B processor) were provided every 6 months during the operational phase of Aeolus.



The Aeolus End-to-End Simulator (E2S)

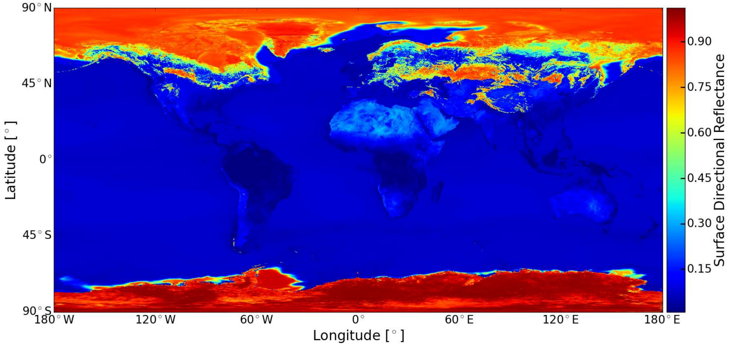
Orbit + Pointing → Atmosphere + Ground → ALADIN instrument → Data formatter → L0 + L1A + L1B processor

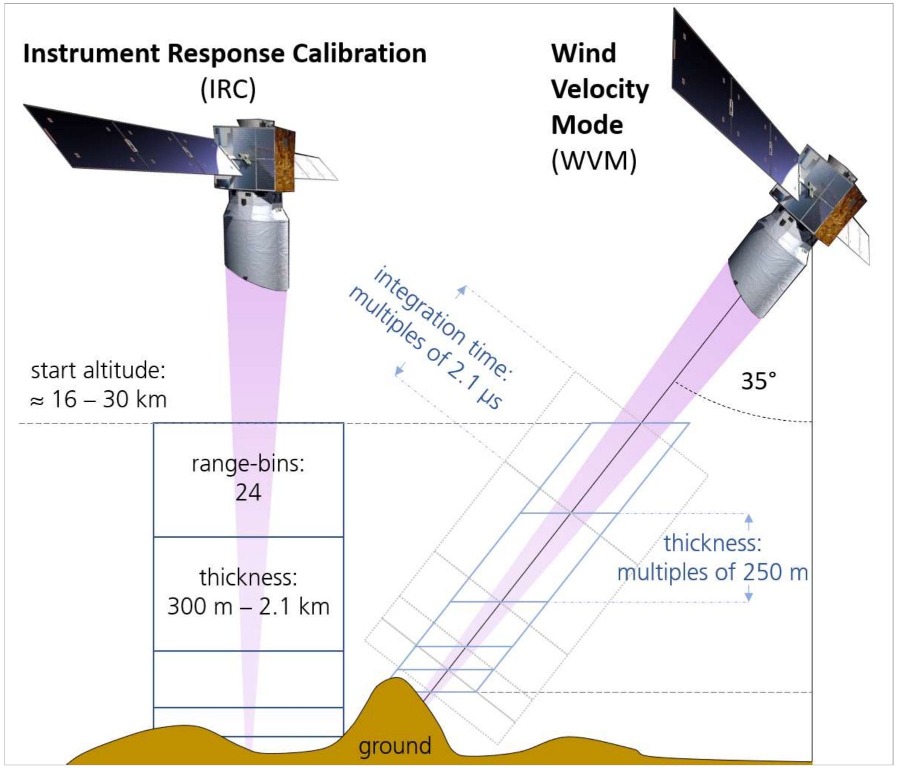
Aeolus orbit and DEM



UV surface reflectance

(ADAM database)





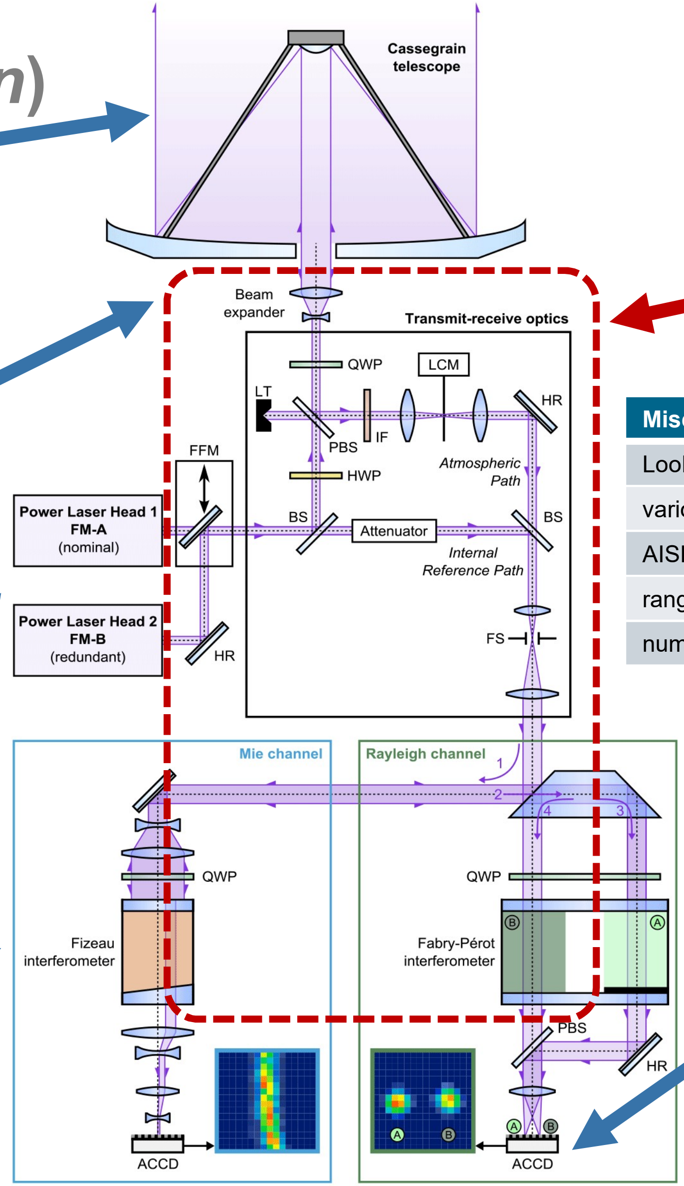
E2S parameters (*selection*)

Atmosphere and Ground	
wind	altitudes
temperature	cloud thickness
pressure	cloud backsc. & extinct.
molec. backsc. & extinct.	DEM
aeros. backsc. & extinct.	albedo

Satellite and Structure
telescope aperture
receiver FOV
pointing errors
transmission transmitter chain
transmission receiver chain
pointing errors
nominal off-nadir angle

Laser	
wavelength	pulse energy
linewidth	integration times

Fizeau spectrometer	
peak transmission	fringe tilt
FWHM / FSR	geometrical factor



Lux et al. (2021) AMT

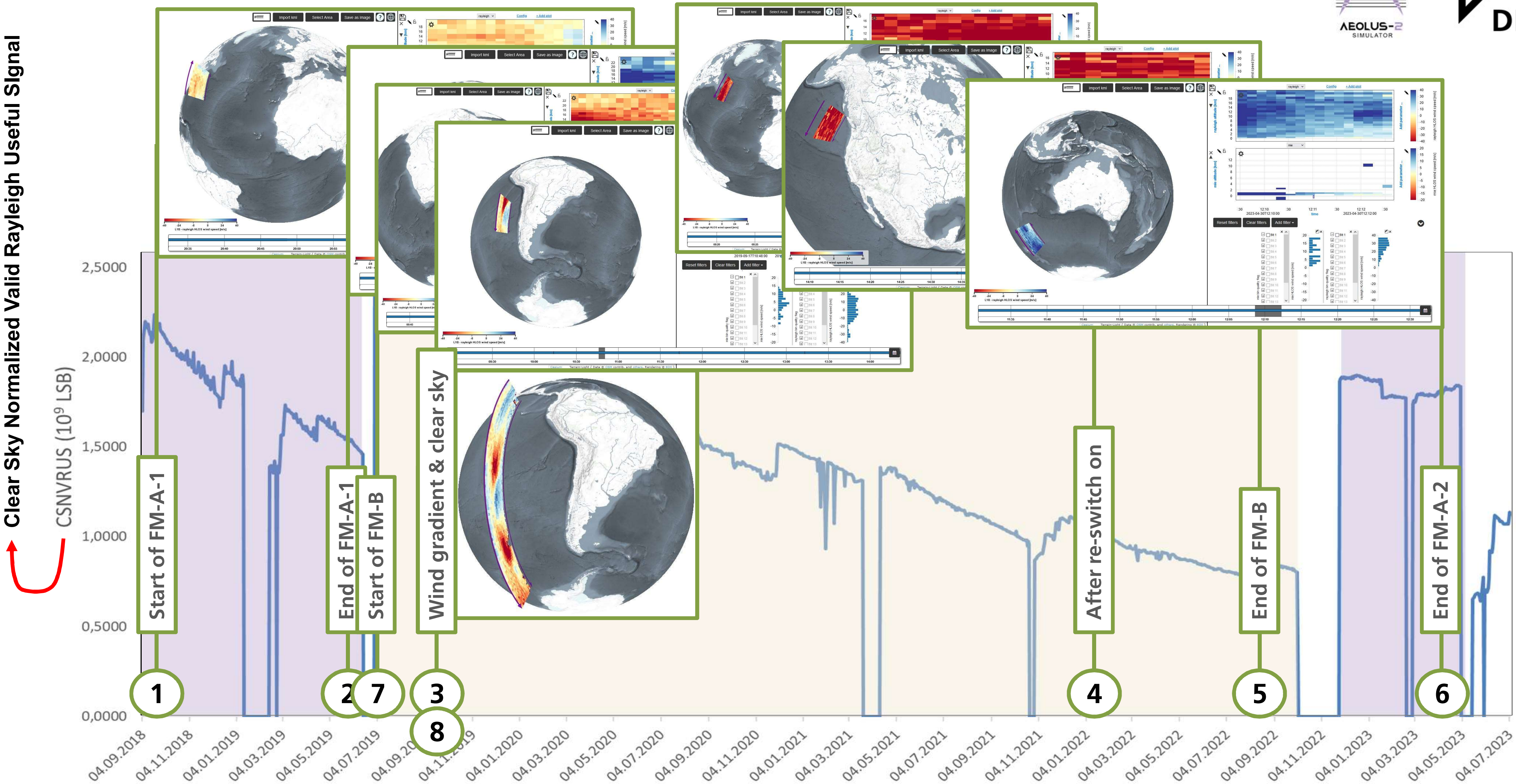
Only single transmission values!
→ „weakest" part of the simulator
→ no simulation of angular dependent illumination

Miscellaneous	
Look-Up-Table (= onboard DEM)	constants
various noise sources	master clock rate
AISP defaults parameters	delay times,
range-dependent bias	frequency arrays
number of pulses & measurement	sub-resolution

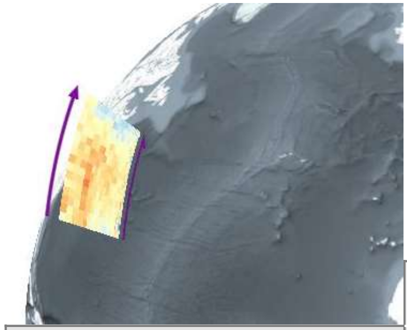
Fabry-Perot spectrometer
peak transmission (direct reflected)
spectral spacing
FWHM / FSR
gaussian defects

ACCD
quantum efficiency
pixel characterisation (size, noise, …)
tripod transmission
radiometric gain (LSB/e$^-$)
time in memory zone

Scenarios for comparison of Aeolus vs. Simulation

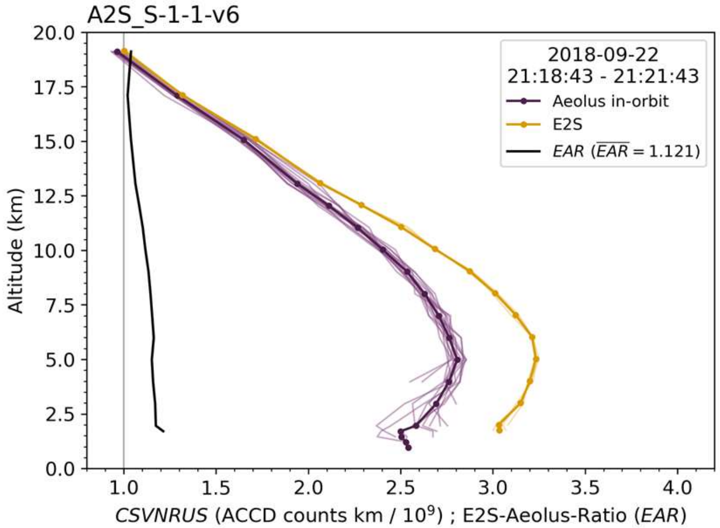


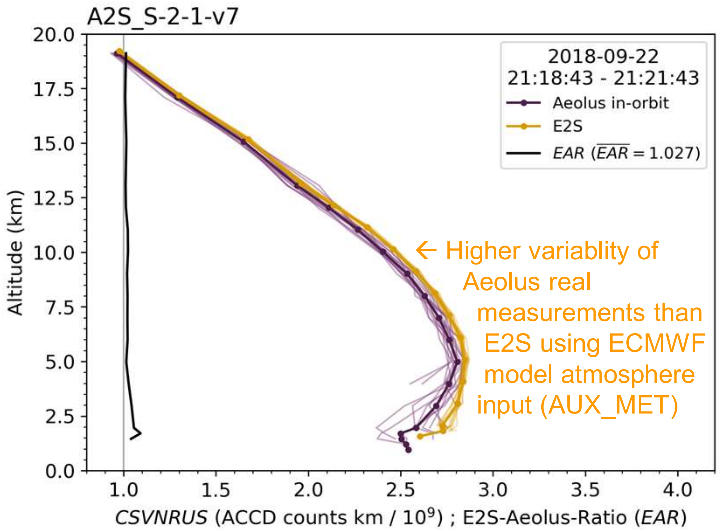
Comparison of Rayleigh useful signal



Scenario
1

	FM-A-1
Date	22.09.2018
NRT Baseline *(L1B Version)*	1B14 *(07.12)*
Pulse energy / mJ	62
Pulses / Measurements	19 / 30





- **U.S. Standard Atmosphere**

- constant wind profile
- median aerosol profile*
- adapted dynamic range, noise, …

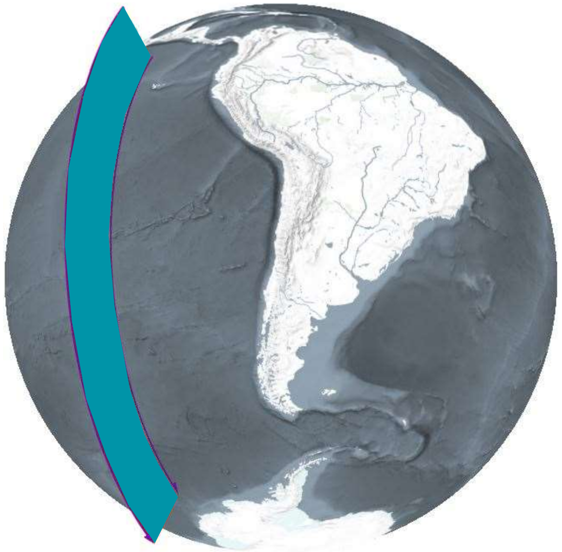
- **+ atmosphere from ECMWF:** wind, temperature and pressure → and derived molecular backscatter and extinction
- + transmission values

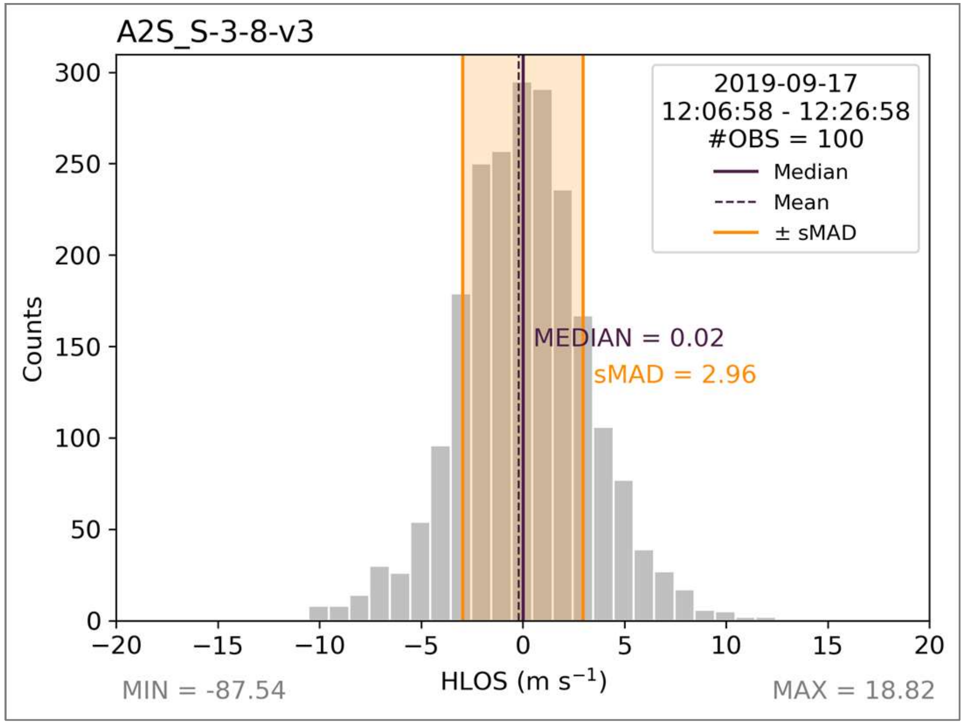
- **Simulator-to-Aeolus-ratio ≈ 1**
- Only very weak altitude dependence

* ***ESA***, *Reference Model of the Atmosphere (1999)*

Comparison of Rayleigh wind random error

8 Laser	FM-B
Date	17.09.2019
NRT Baseline *(L1B Version)*	1B12 *(07.10)*
Pulse energy / mJ	61.5
Pulses / Measurements	19 / 30





- **U.S. Standard Atmosphere**

- constant wind profile (0 m/s)
- median aerosol profile*
- adapted dynamic range, noise, transmissions, …

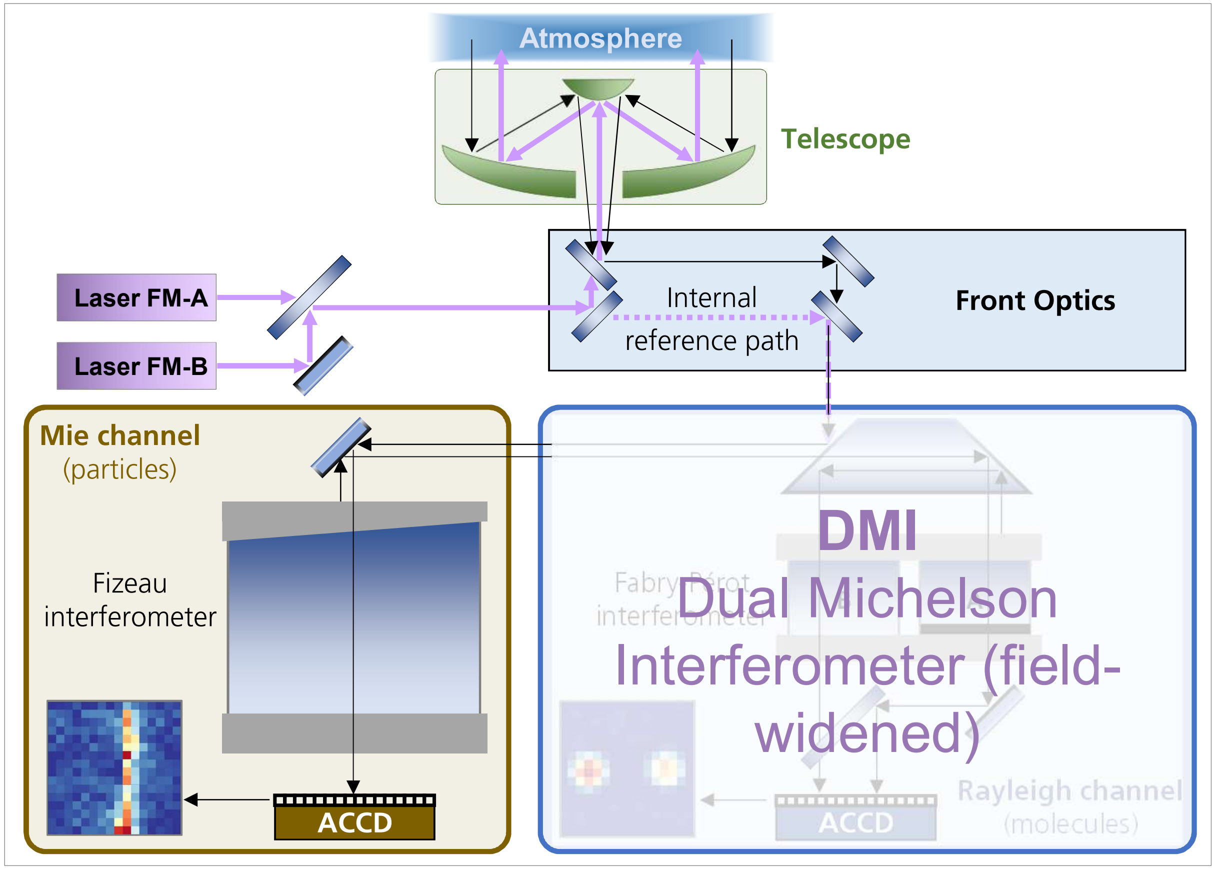
- **Bias**: almost **0 m/s** reached
  (mainly by adapting the calibration and noise parameters)

- **Random** error (HLOS):
  - **E2S**: (vs. median from 0-profile)
    sMAD ≈ 3.0 m/s
  - **Aeolus**:
    sMAD ≈ 3.4 m/s
    (from ECMWF O-B, corrected for B-error)

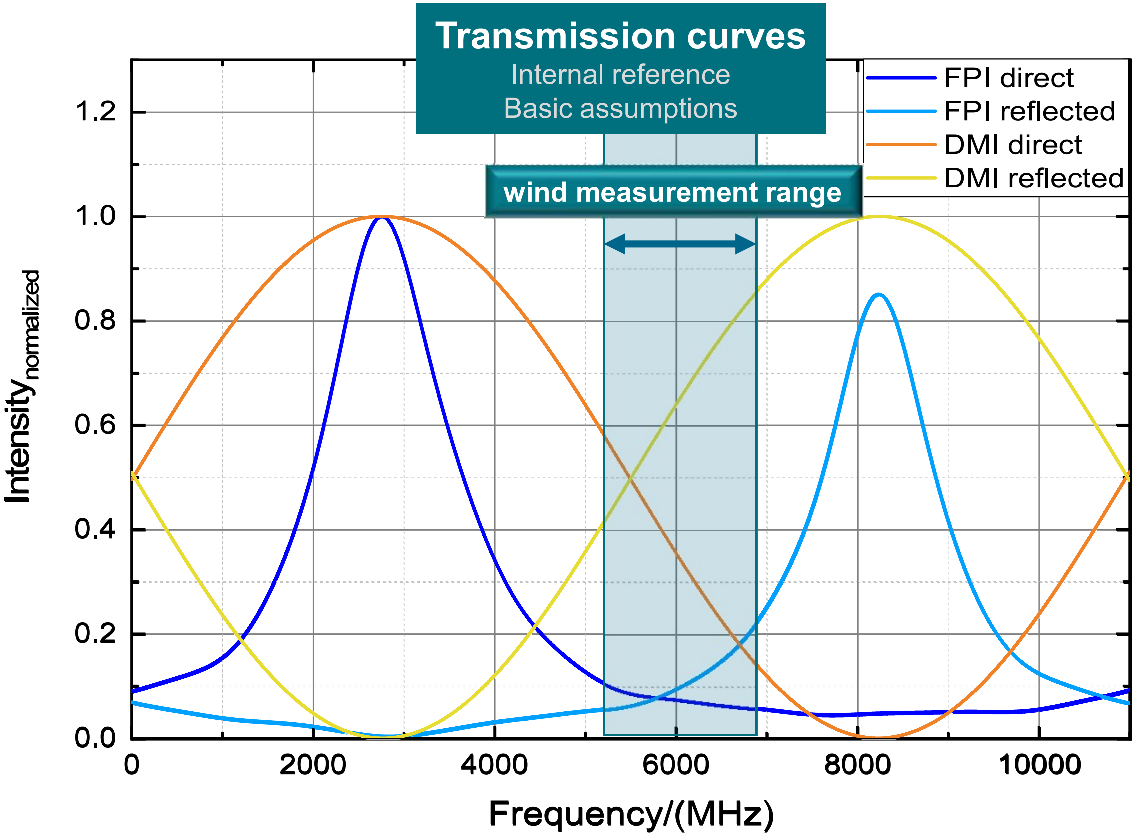
* ***ESA***, *Reference Model of the Atmosphere (1999)*

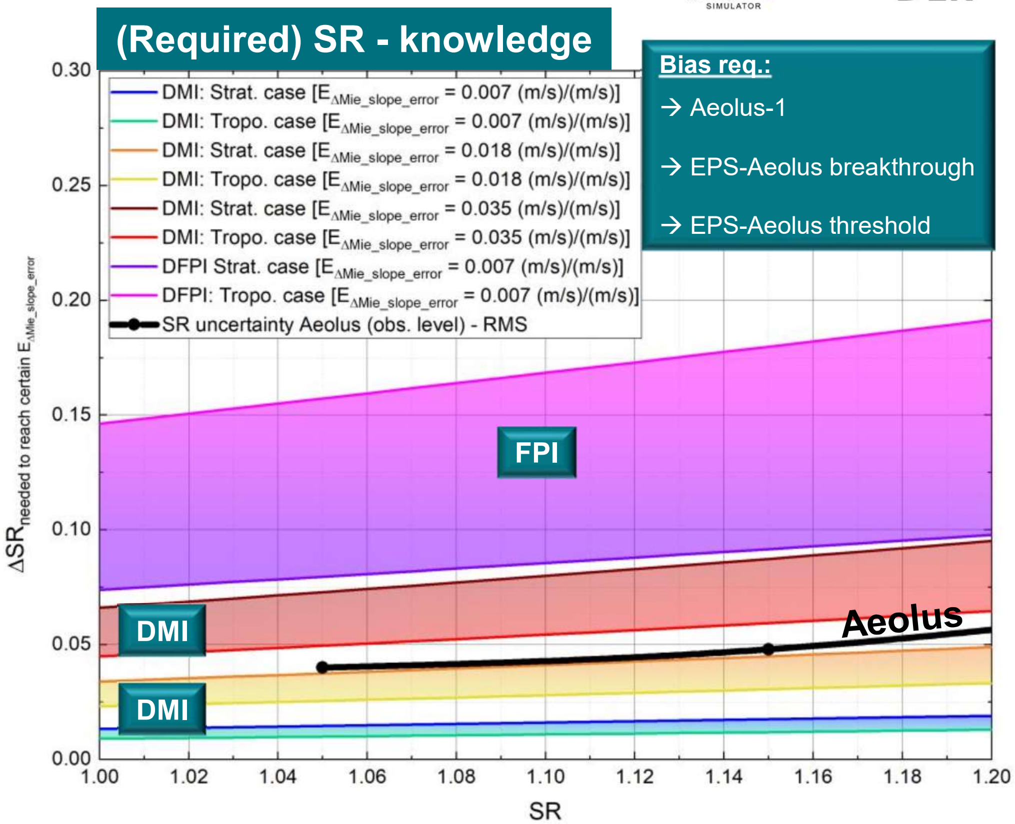
Dual Michelson Interferometer (DMI) & Mie cross-talk

- **Mie contamination on Rayleigh** signal is a significant error contributor for 1.3 < SR < 2.0 (depending on atmospheric T)
- → In regions where Mie SNR is too low to derive accurate Mie winds (**intermediate SR regime**) a "correction" of Rayleigh winds is needed (critical for DMI)
- → Either **correction** of contamination or **flagging** of observations
- Both approaches need determination of **scattering ratio** from EPS-Aeolus data (low accuracy from NWP)
- **EPS-Aeolus** will provide **backscatter information** → Influence of Mie contamination can be corrected.
- But: **How accurate** does the backscatter information need to be to meet the EPS-Aeolus wind **error requirements**?
- → **Tasks**:
  1. *Model the DMI (transmission & responses)*
  2. *Determine the wind bias and assess a potential error correction scheme*
  3. *Compare to Aeolus DFPI*



DMI vs. Fabry-Pérot-Interferometer (FPI)





→ Mie contamination plays only a minor role for the FPI

→ With Aeolus-like SR-knowledge the Mie sensitivity error would be ≈ 0.018 m/s / (m/s) → 1.8 m/s on 100 m/s range

→ The error wind speed dependent

Witschas *et al. (2023) AMT /* ***Herbst and Vrancken*** *(2016) Appl. Opt. /* ***Dabas*** *et al. (2008) Tellus /* ***ESA*** *tender, Performance requirements*

Summary

- DLR has ≈ **20 years of experience** with airborne wind lidars

- **Good correlation** achieved for Rayleigh clear air **signal** profiles simulated by the E2S and measured by Aeolus
- **Reasonable** results achieved for L1B Rayleigh wind **random errors** (3 m/s vs. 3.4 m/s) for a first case
- **Next step**: simulate **EPS-Aeolus** performance with E2S by updating the respective (and known) parameters and tuning to required wind random error specification and comparing performance of Aeolus to (expected) EPS-Aeolus
- **Future E2S improvements**: RSP spots, Fizeau illumination, Rayleigh solar background simulation, end-to end verification, …

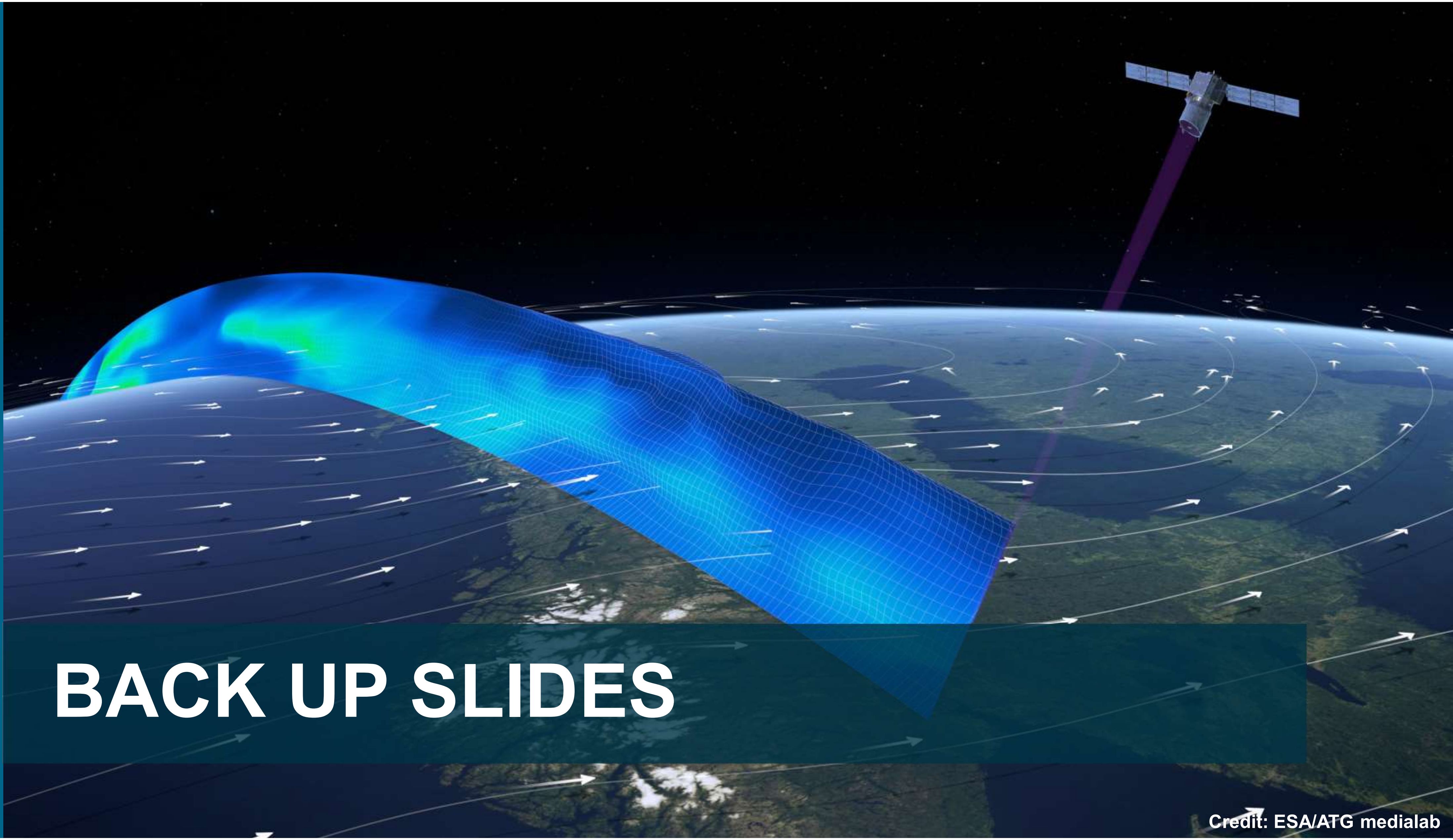
- A representative **DMI simulator** (as one option planned for EPS-Aeolus) was developed in the current study.
- The DMI **performance** was investigated and compared to the Aeolus FPI performance

- **Final step**: Validate real EPS-Aeolus measurements by E2S simulations and A2D(2G) measurements

The funding for this study was provided by EUMETSAT

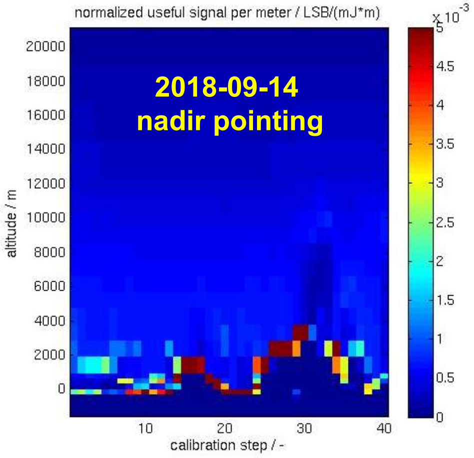

Thank you for your attention!

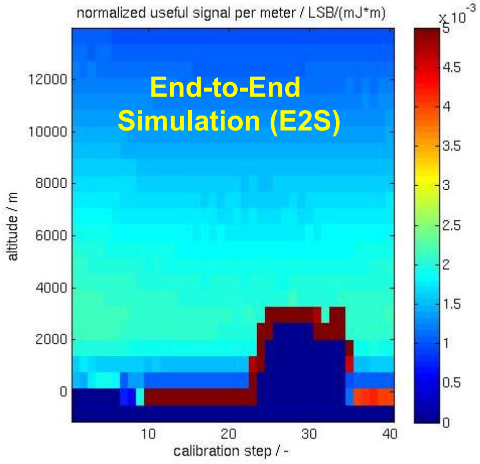
BACK UP SLIDES

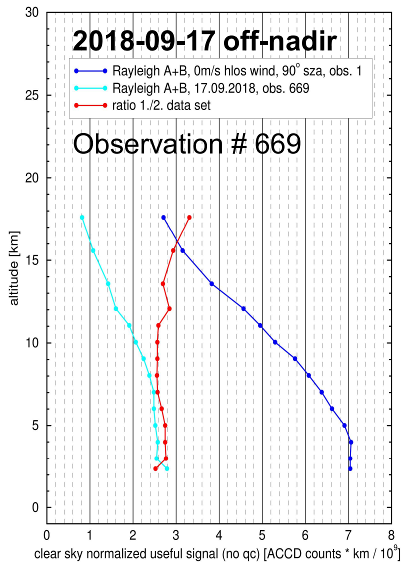


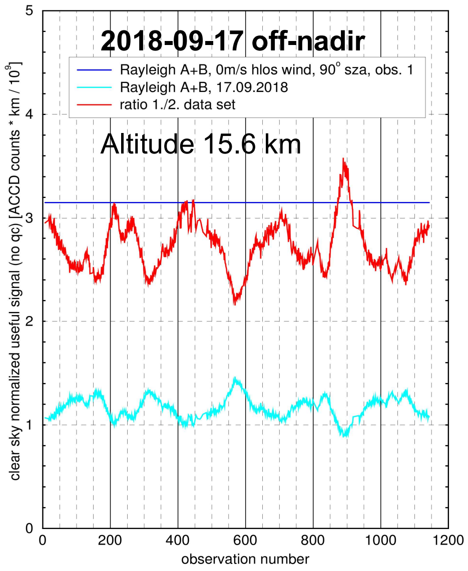
Credit: ESA/ATG medialab

Radiometric performance assessment – Aeolus vs. E2S









- Use of **molecular Rayleigh backscattering** above clouds for instrument radiometric performance verification
  - → only depending on atmospheric density (temperature)
  - → low uncertainty
- **Different approaches** (nadir / off-nadir viewing) and different tools at different teams show a factor of about 2.5 to 3 **lower Rayleigh signal** levels compared to pre-launch expectations (derived from End-to-End Simulations using default settings)
- Signal levels for high-albedo (ice) **ground returns** are even lower by factor 2.5 to 5.0 (Mie/Rayleigh)
- A factor 2.5 – 3.0 lower atmospheric signal signal increases **wind random error** by a factor of 1.6 – 1.7
- Signal loss potentially caused by a combination of beam clipping, characteristics of the telescope and the transmit-receive optics, and atmospheric turbulence.

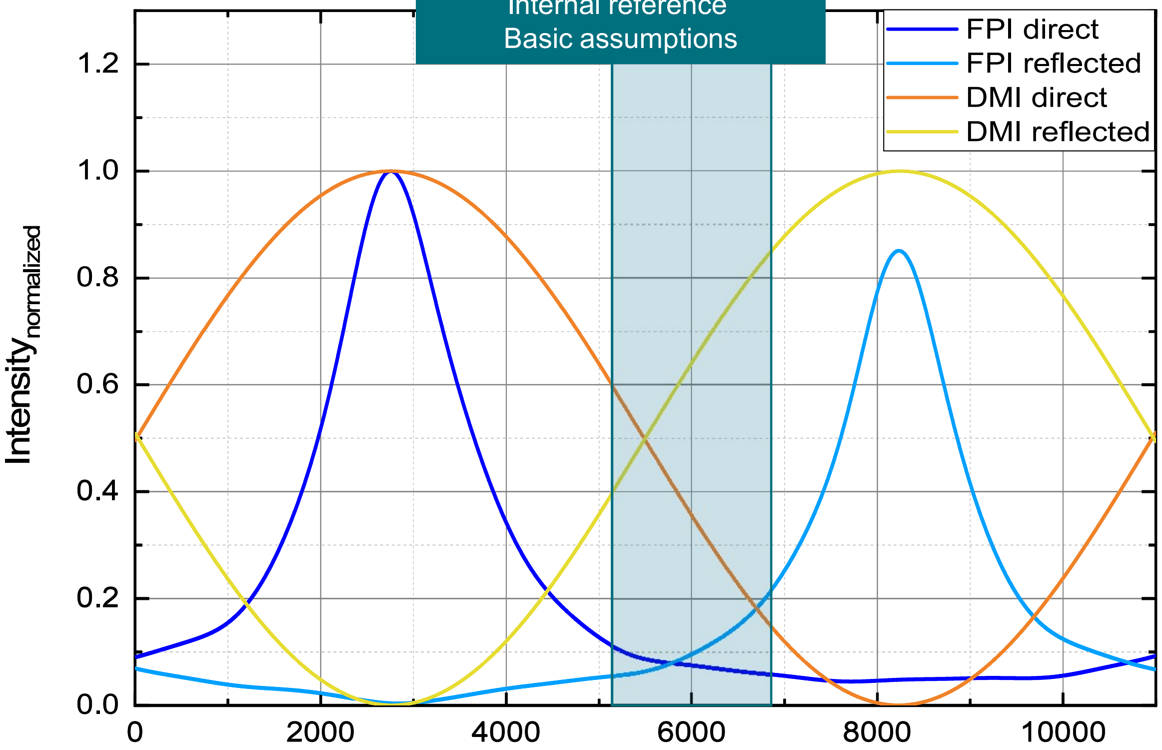
Limitations of the current version of the Aeolus End-to-End Simulator (E2S)

- As the **E2S has not been updated** since the launch of Aeolus → Feed the **knowledge gained from in-orbit operations** back into the simulator and produce realistic signals depicting real Aeolus observations
- Usage of **EO-CFI** for orbit and viewing geometry of EPS-Aeolus
- No **DEM Look Up Table** existing yet for EPS-Aeolus
- Not representing the full **complexity** of the Fizeau and Double Fabry-Perot interferometers
- **DMI** can only be integrated in the future
- No standard option to insert information about **depolarization** by particles
- Reliance on the ADAM **albedo** map and the inherent uncertainties.
- Inability to simulate certain types of **bias sources** (e.g. primary mirror temperature)

DMI vs. Fabry-Pérot-Interferometer (FPI)

$$R = \frac{A-B}{A+B}$$

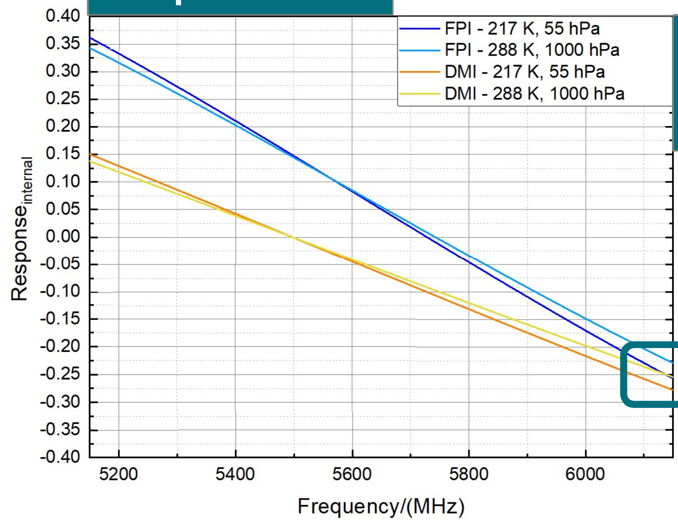
Transmission curves
Internal reference
Basic assumptions



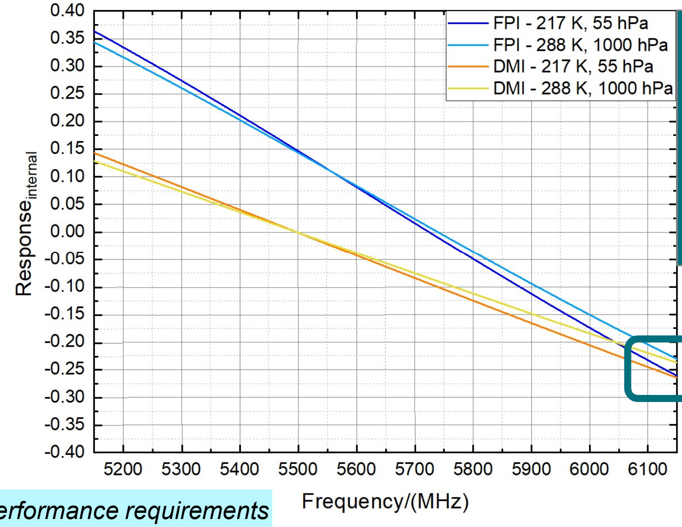
A = transmitted intensity

B = transmitted intensity

Response to …



broad-band molecular signal



broad-band molecular signal
+
Mie contamination

***Witschas** et al. (2023) AMT / **Herbst and Vrancken** (2016) Appl. Opt. / **Dabas** et al. (2008) Tellus / **ESA** tender, Performance requirements*