INITIAL ASSESSMENT OF THE PERFORMANCE OF THE FIRST WIND LIDAR IN SPACE ON AEOLUS

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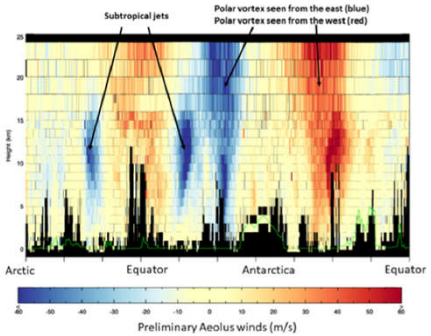
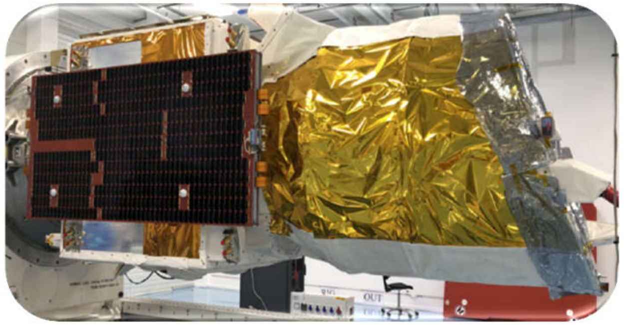
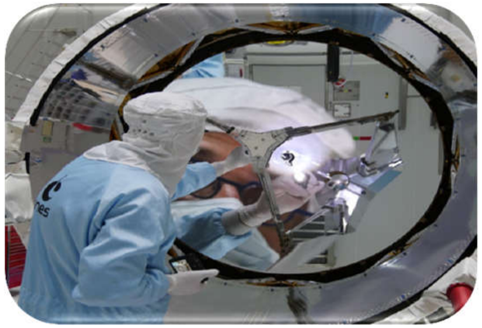
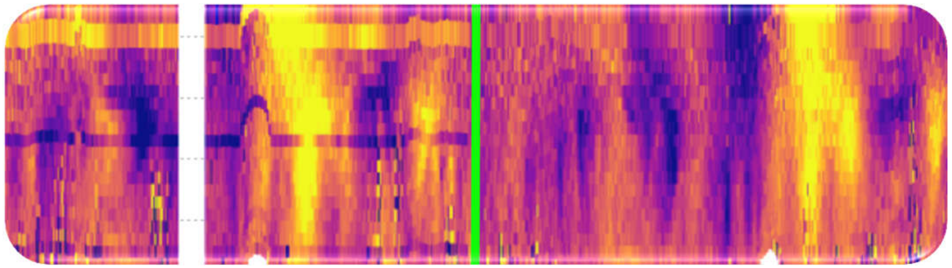


Overview

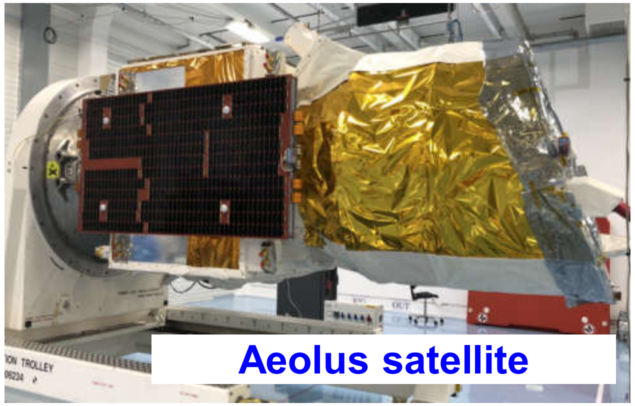
- ➢ First results from Aeolus and ground-based validation
- ➢ ALADIN performance and random errors
- ➢ Main causes for systematic errors and their correction

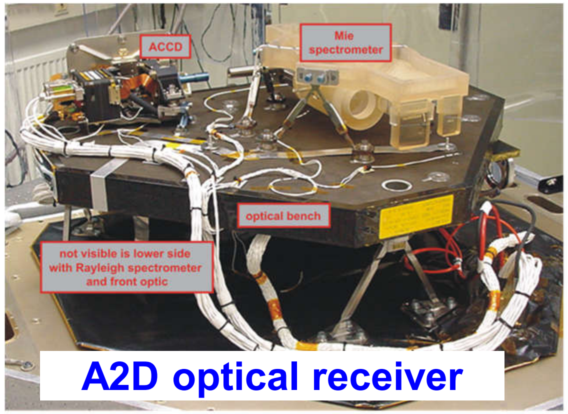


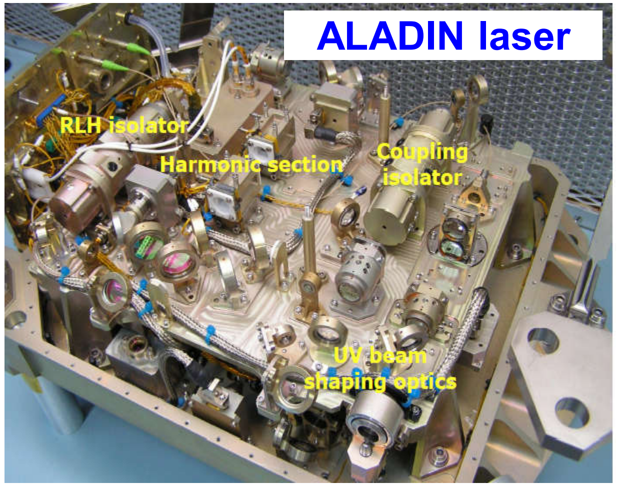


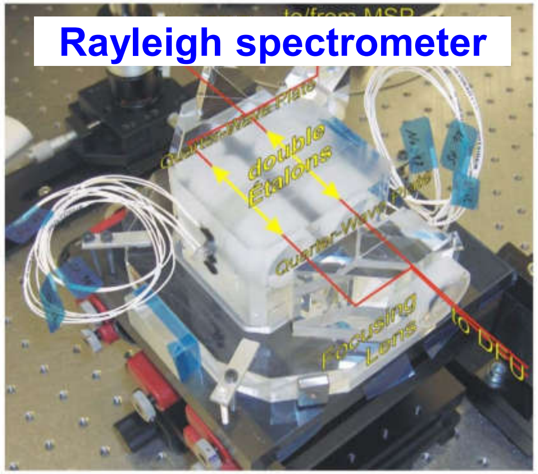


ALADIN – the first wind lidar in space since August 2018









- **First European lidar** in space after 20 years of development challenges
- **First wind lidar and HSRL in space** – worldwide unique mission
- **Highest power-aperture** product for a lidar in space (40-80 mJ / 50 Hz / Ø 1.5 m)
- **High-power, ultraviolet (UV) laser** in space (@ 354.8 nm) with stringent requirements on frequency stability of 6-8 MHz (shot-to-shot)
- **Doppler wind lidar** principle – straightforward but incredible small effect

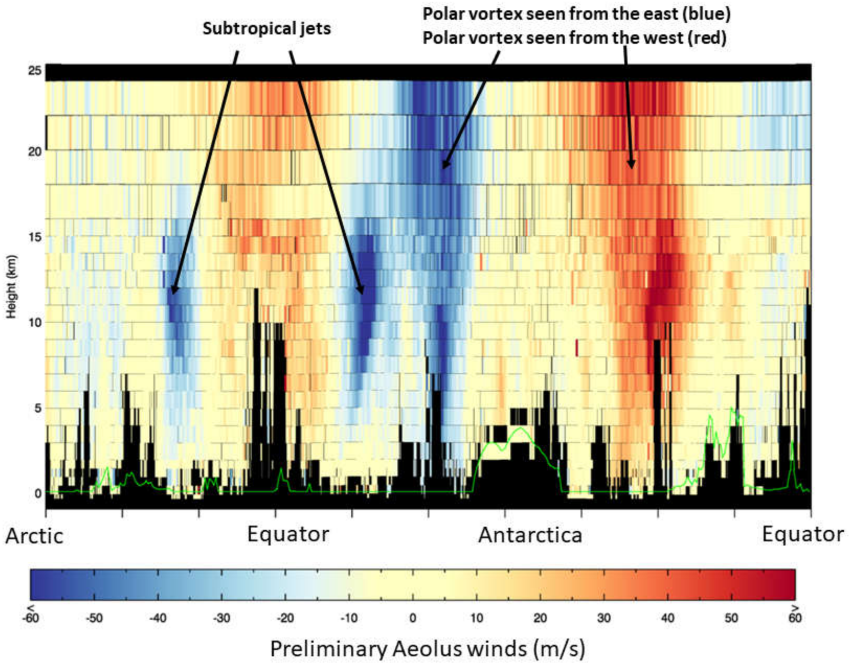
Doppler-Shift: $\Delta f = 2 f_0 \frac{v_{LOS}}{c}$

relative Doppler shift $\Delta f/f_0 \approx 10^{-8}$
1 m/s (LOS) ⬄ 5.64 MHz ⬄ 2.37 fm

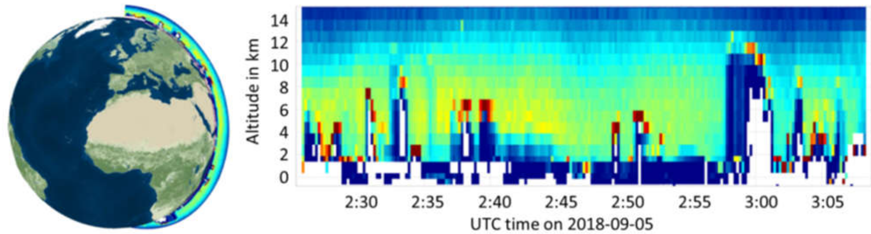
First wind measurements after 3 weeks in orbit

Launch on 22/08/2018

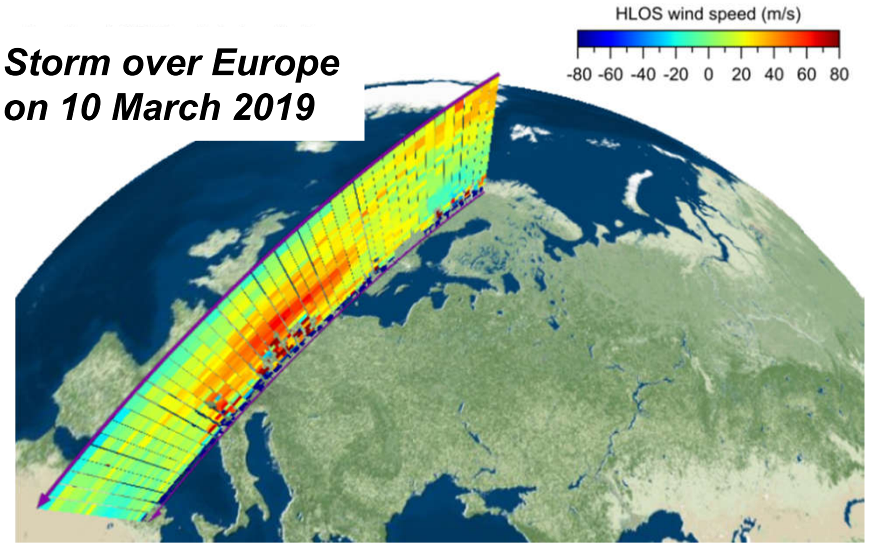
First wind data published on ESA website on 12 September 2018



First Rayleigh backscatter signals from 5 Sep 2018



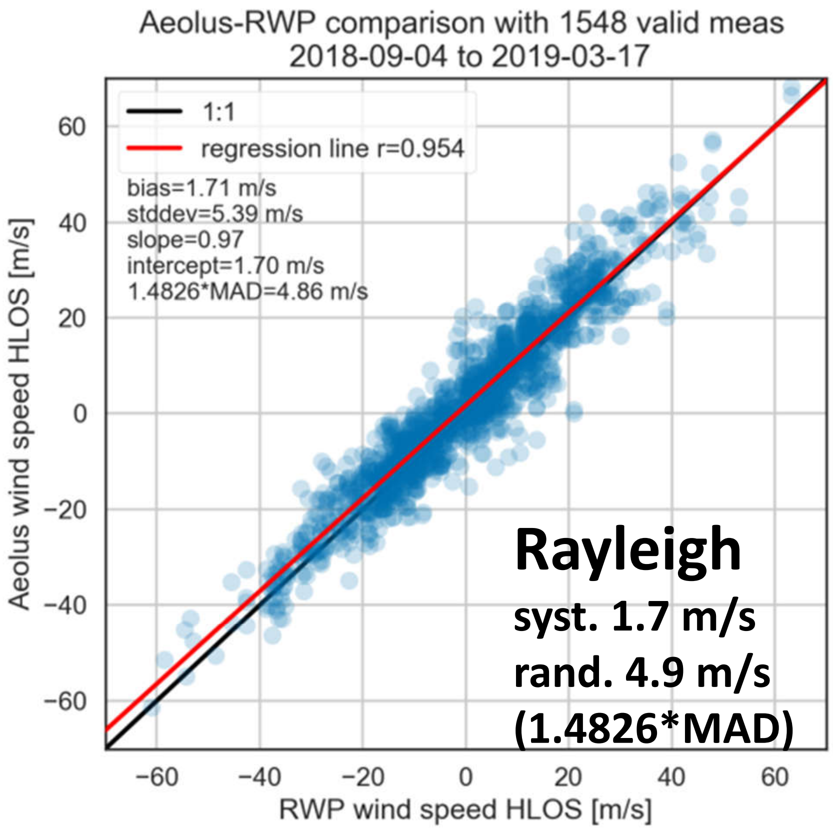
Storm over Europe on 10 March 2019



Plots withVirES for Aeolus

Comparison of Aeolus to DWD Radar Wind Profiler

Comparison from Sept 2018 – mid March 2019 for 4 DWD windprofilers in Germany within 100 km



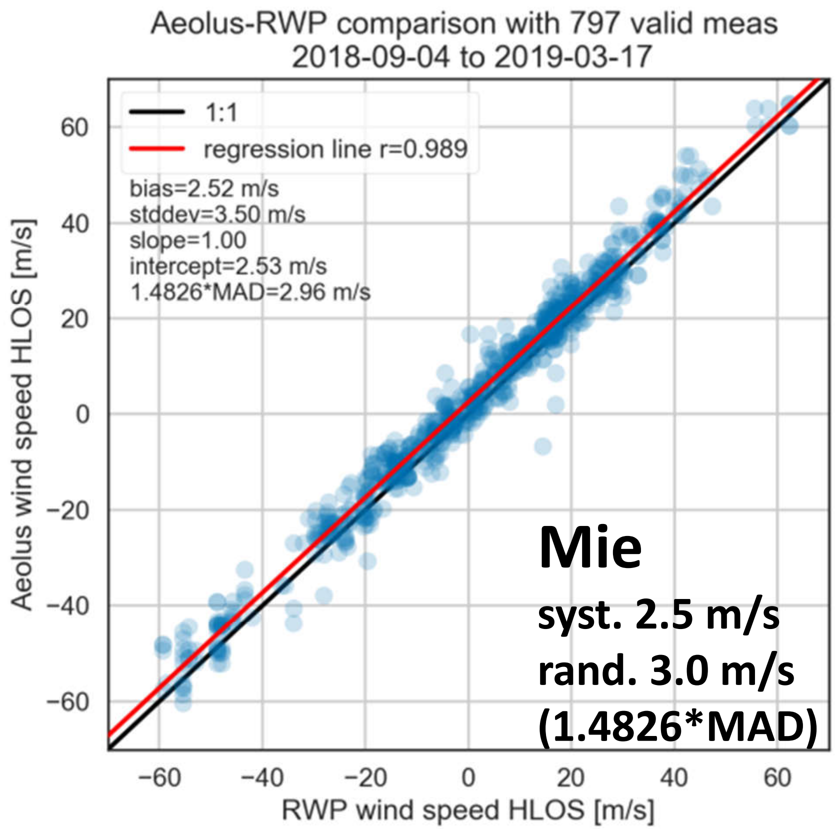
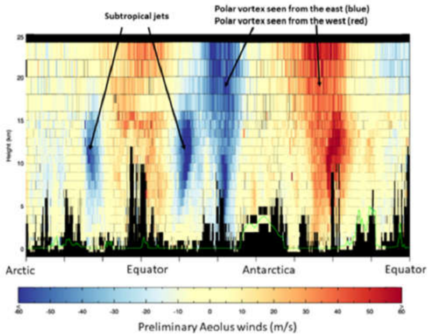
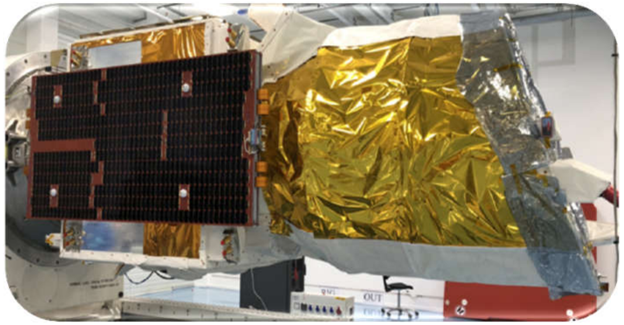


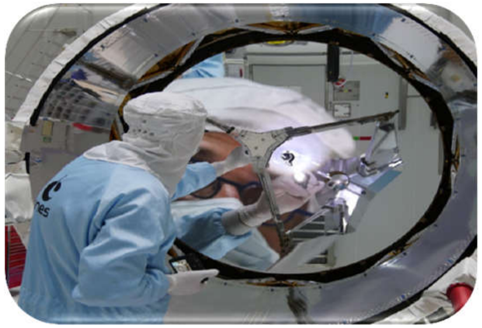
Fig. courtesy A. Geiss (LMU)

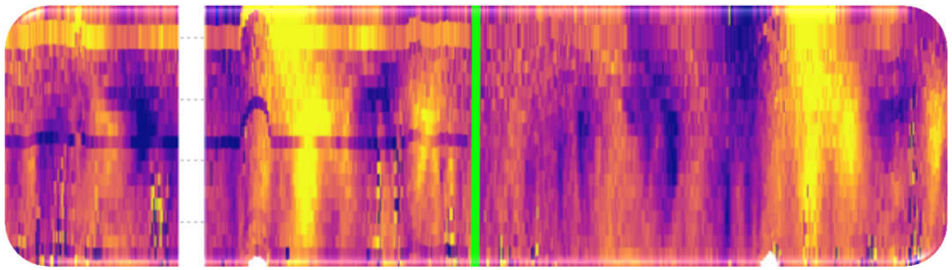
EVAA Project coordinated by LMU-MIM with DWD and TROPOS in cooperation with DLR

EVAA: Experimental Validation and Assimilation of Aeolus Observations





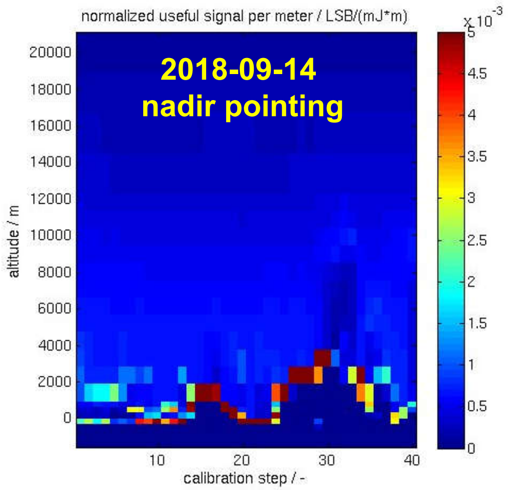


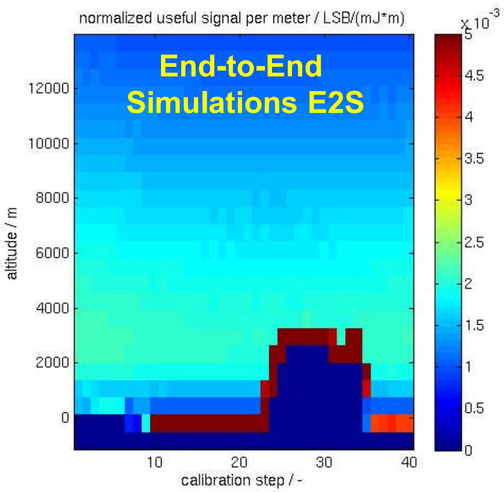


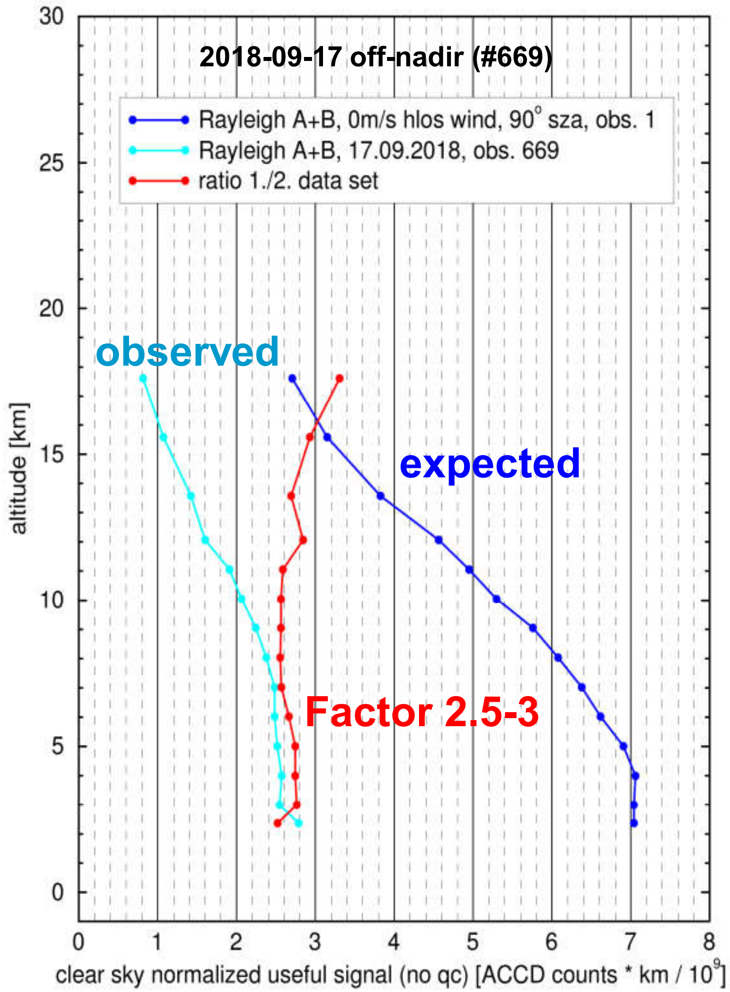
Overview

- ➢ First results from Aeolus and ground-based validation
- ➢ **ALADIN performance and random errors**
- ➢ Main causes for systematic errors and their correction

What causes enhanced Rayleigh wind random errors?



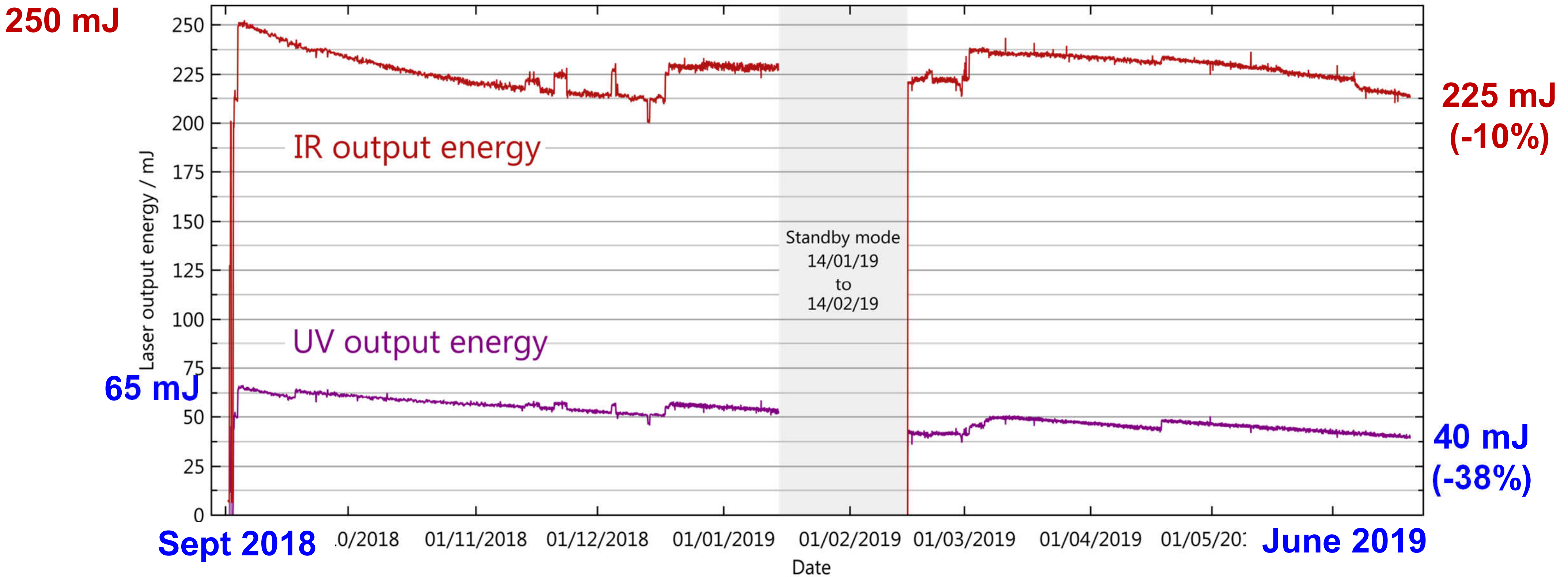




- **Lower Rayleigh backscatter signals by factor of 2.5 – 3.0** => higher random errors by factor 1.6 - 1.7 resulting in 4 m/s Rayleigh wind random error (L2B O-B)
  - **Lower laser energy** of 50 mJ to 65 mJ than expected of 80 mJ: factor 1.23 to 1.60
  - **higher laser divergence**, which is clipped at the instrument field stop limiting the field-of-view to only 18 µrad
- Switch to second laser on June 26, 2019 with a target energy of 80 mJ => Rayleigh random error 3 m/s

Fig. U. Marksteiner, K. Schmidt (DLR)

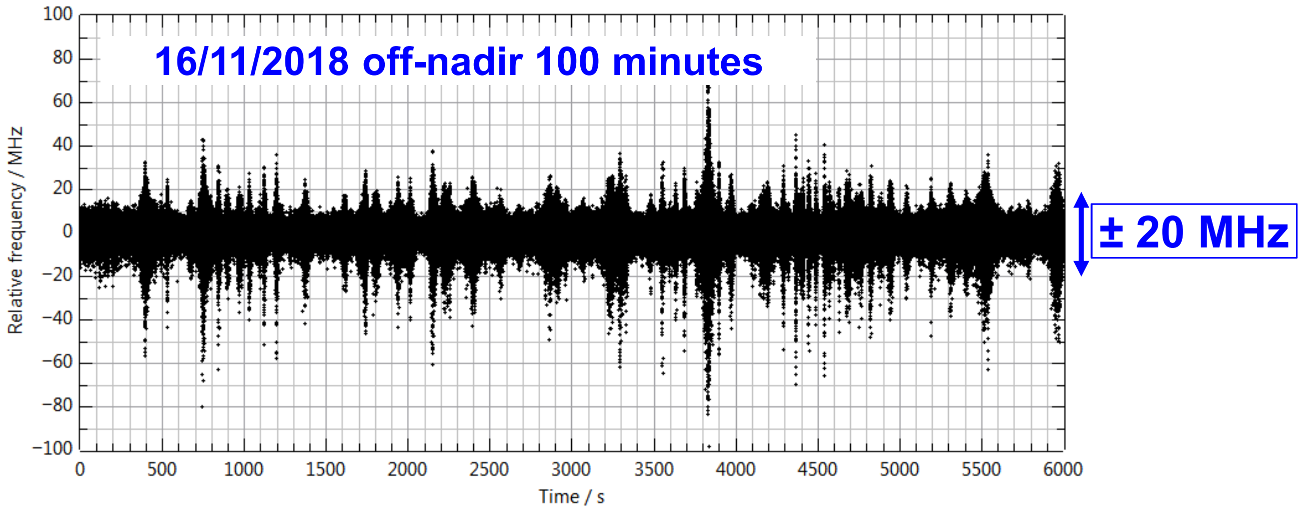
Laser energy evolution in IR and UV over 10 months

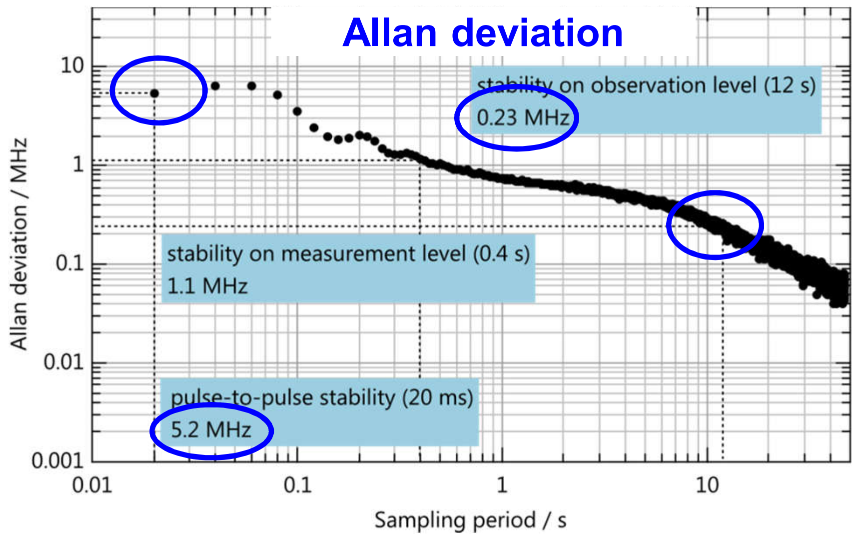


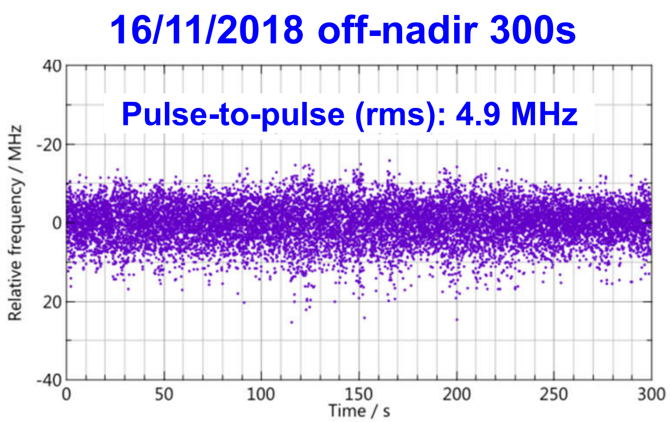
- **First time of successful operation of a high-power UV laser in space over 10 months**
  => proves concept for oxygen cleaning approach for laser optics
- **65 mJ** for first laser achieved, UV energy decreases at a rate of about **1 mJ per week:**
  but some issues with laser internal photodiode, optimizations can increase energy levels

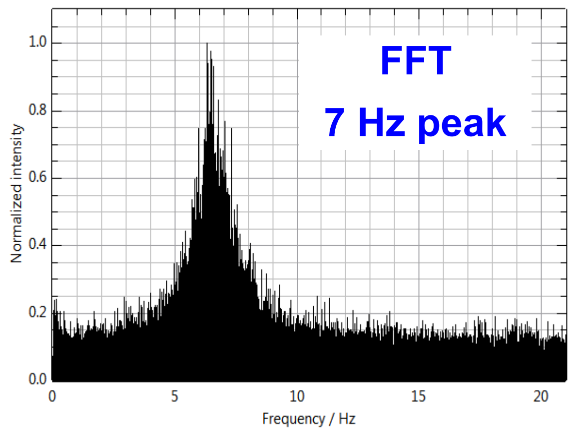
Fig. O. Lux, Ch. Lemmerz (DLR)

Laser frequency stability of 5-7 MHz (UV) achieved



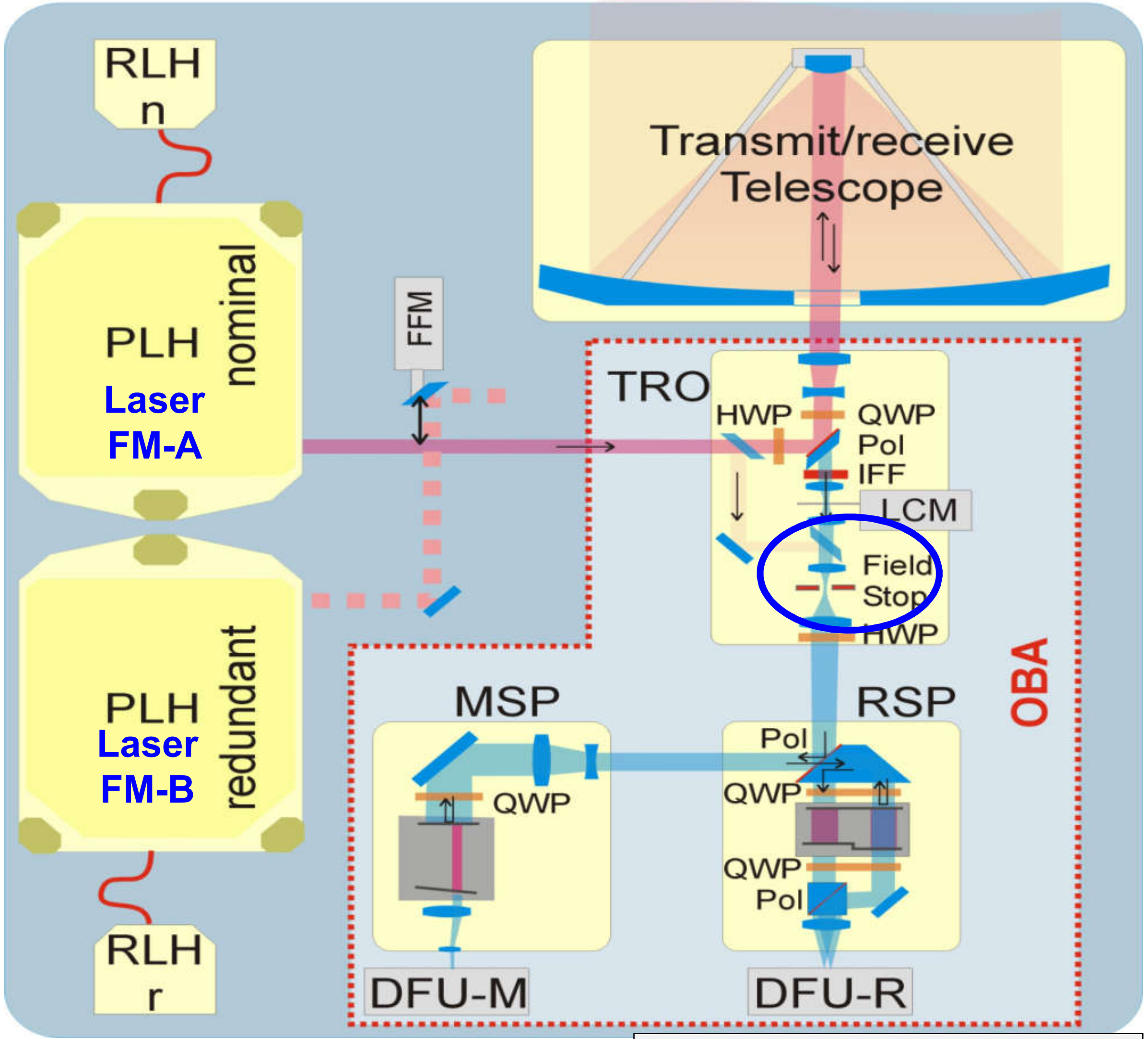






- **Very good in-orbit performance achieved with pulse-to-pulse 5-7 MHz (UV, 1.7-2.3 MHz IR, rms)** with periodic oscillation of 7 Hz , 0.23 MHz (UV) for 12 s observations achieved
- **Laser resonator of length 0.8 m actively stabilized to 5.6 nm** (10^{-8}) for 5.6 MHz (= 1 m/s)
- **Mie spectrometer is used as high-precision laser spectral analyser** for single shots
- Enhanced frequency jitter up to 100 MHz (p-p)

Fig. O. Lux, Ch. Lemmerz (DLR)



ESA (2008): Aeolus Science Report

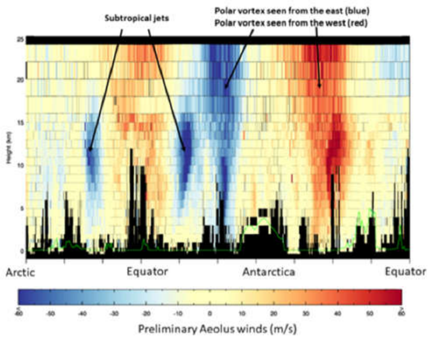
ALADIN optical setup

- lower laser energy of 50-65 mJ vs. 80 mJ accounts for factor 1.2 to 1.6
- higher laser beam divergence and non-perpendicular incidence angle resulting in clipping of backscatter signal at receiver field stop => accounts for factor ≈ 2
- field stop limits field of view to only 18 µrad in the atmosphere => small footprint of Ø 7 m on ground
- no indication of optics degradation in receive path
- Rayleigh random error is dominated by signal shot noise and by seasonal and orbital varying solar background

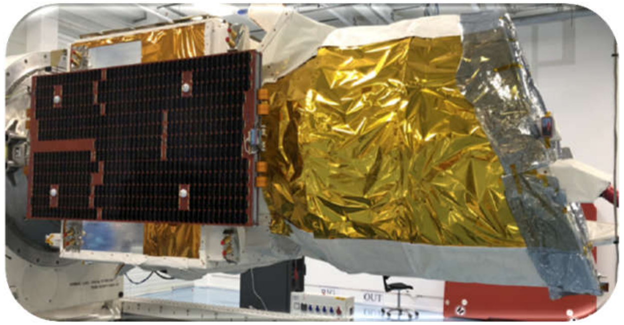
View into the ALADIN Ø1.5 m telescope

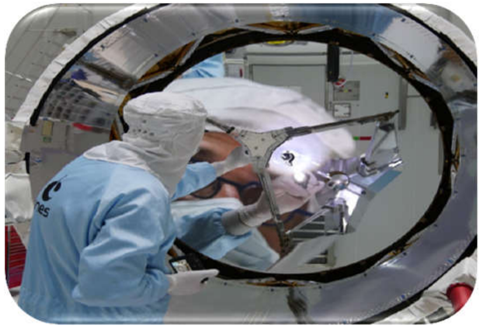
from Aeolus blog https://aeolusweb.wordpress.com/

Overview

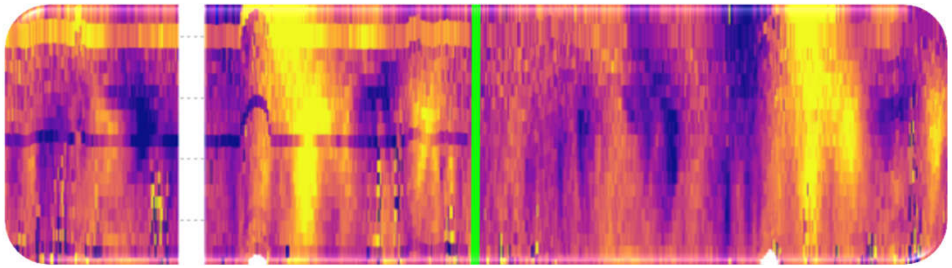


- First results from Aeolus and ground-based validation



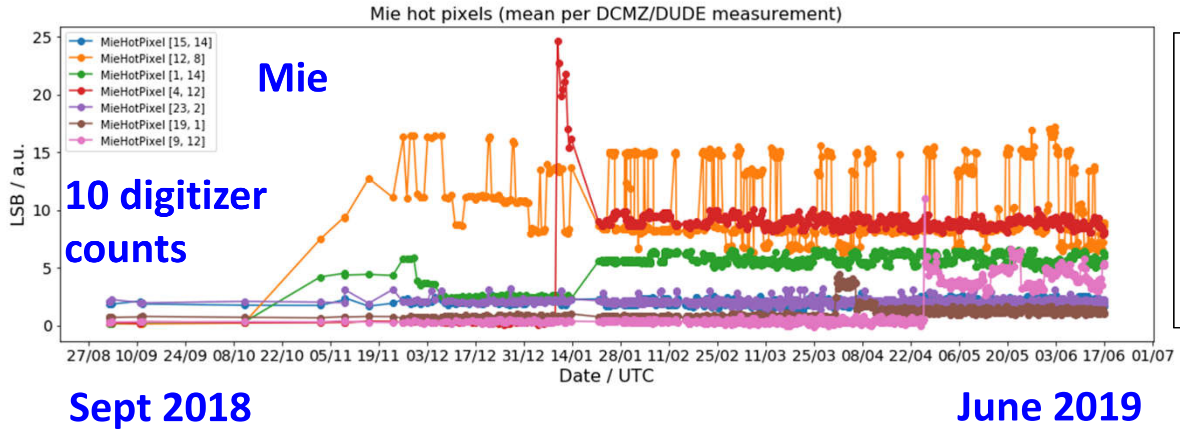


- ALADIN performance and random errors

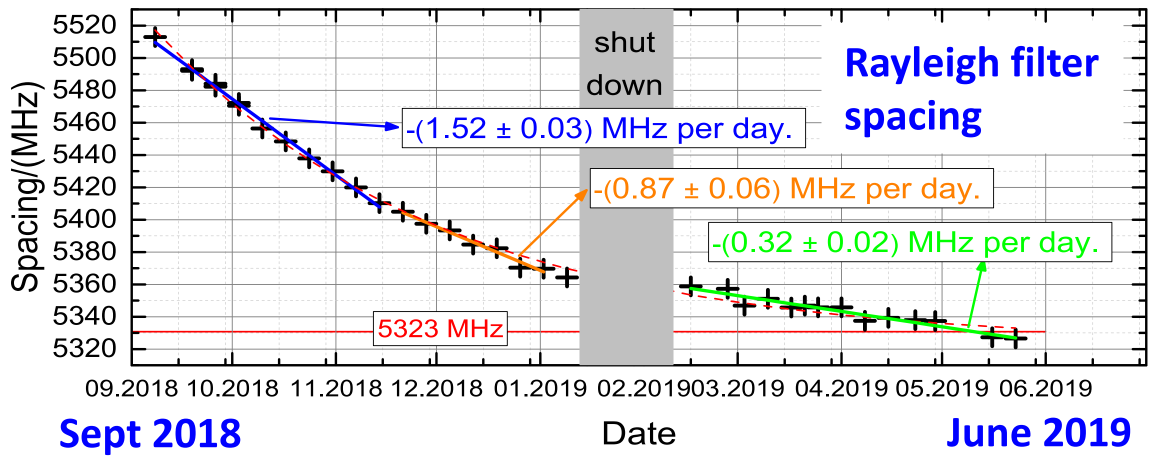


- **Main causes for systematic errors and their correction**

What causes the systematic errors?



Systematic dark signal offsets with 10^{-3} to 10^{-4} of signal or 1% -10% of noise



Rayleigh filter A and B spectral difference nominal 2.3 pm = 5460 MHz => change of 0.4 fm/d ($2 \cdot 10^{-4}$ /d)

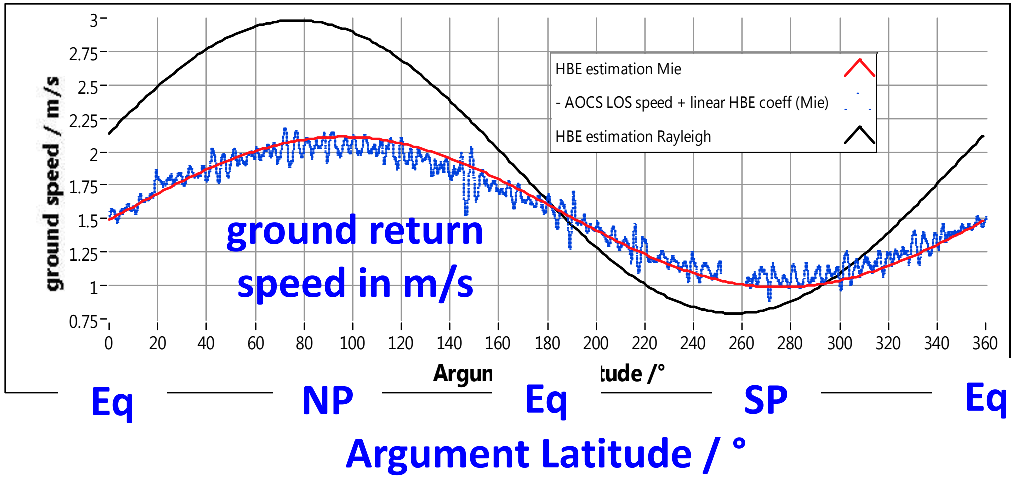
Combination of 3 unexpected error sources with different temporal characteristics

1. Higher dark current rates for some **"hot" pixels** => affects specific range gates; currently 7 on Mie and 8 pixels on Rayleigh ACCD

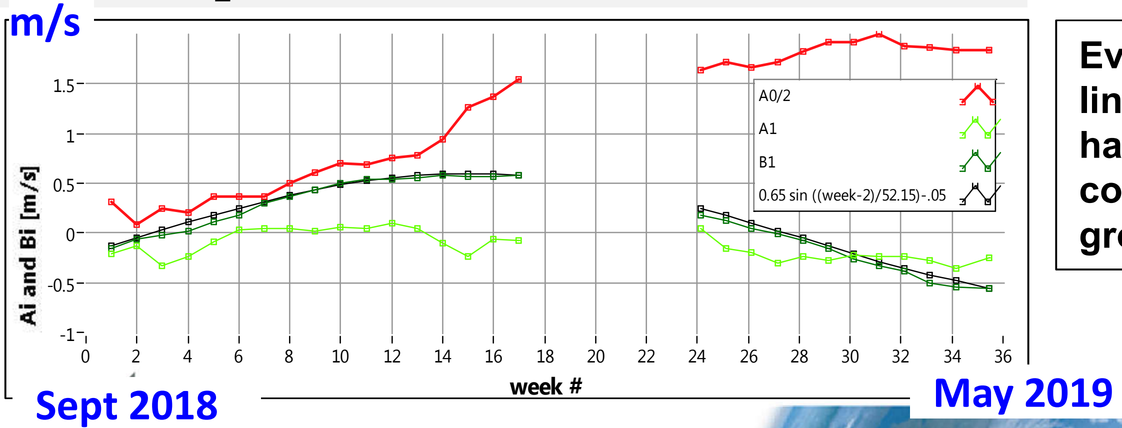
2. **Slow drifts** in the illumination of the Rayleigh/ Mie spectrometers causing a slowly, linear drifting constant bias

Fig. U. Marksteiner, B. Witschas (DLR)

Use of ground-returns to correct for residual bias



$$bias_{HBE} = \frac{A0}{2} + A1\ cosx\ + B1\ sinx; \quad x: Argument\ Latitude$$



satellite speed v_{sat} = 7.5 km/s earth rotation v_{earth} = 465 m/s @ equator

residual satellite LOS speed of 1 m/s => 10^{-4} from v_{sat} or 0.2% of v_{earth}

Evolution of linear and harmonic bias coefficients from ground returns

3. "residual" projection of the **satellite ground speed or Earth rotation on the line-of-sight LOS:** => harmonic variation of bias along the orbit

⇒ Major effort to correct "known" bias sources for both real-time processing and re-processing with ground-returns using a harmonic bias estimator (HBE)

⇒ Anchor atmospheric winds to non-moving ground surface

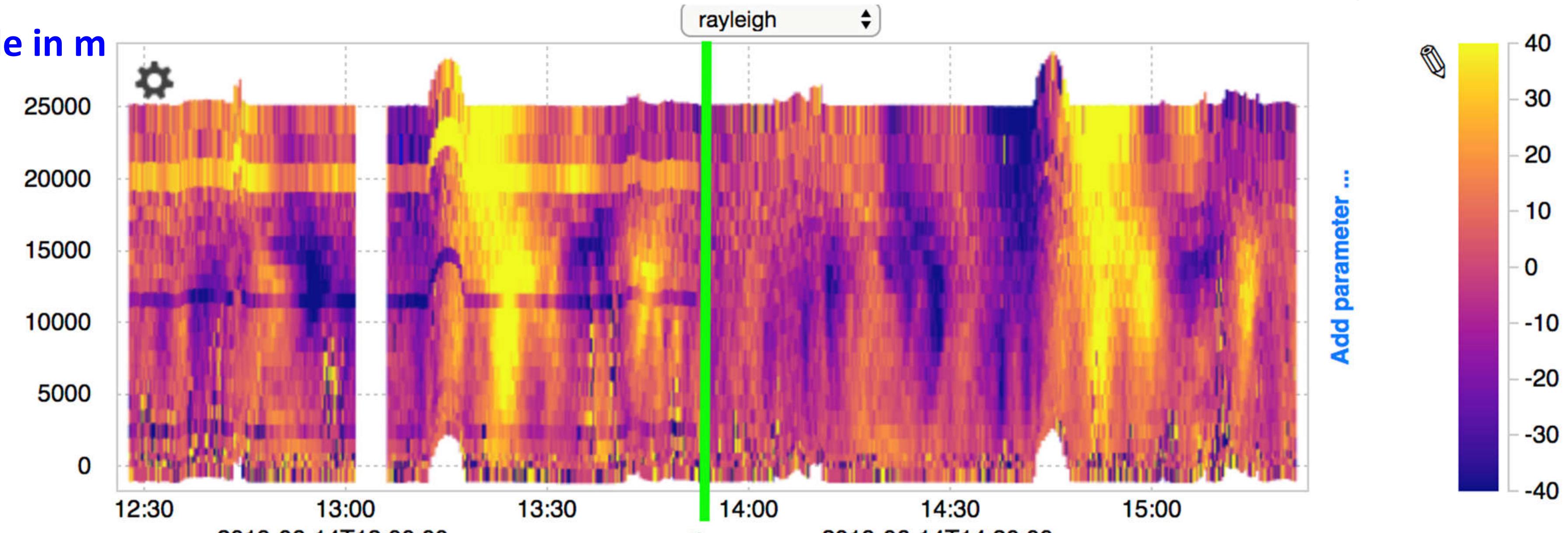
⇒ **New instrument modes introduced, algorithms developed and implemented in operational processors on June, 14, 2019 for correction of "hot pixels"**

Fig. I. Nikolaus (PSol)

Correction of “hot pixels” for ALADIN in June 2019

Rayleigh HLOS wind in m/s

Altitude in m



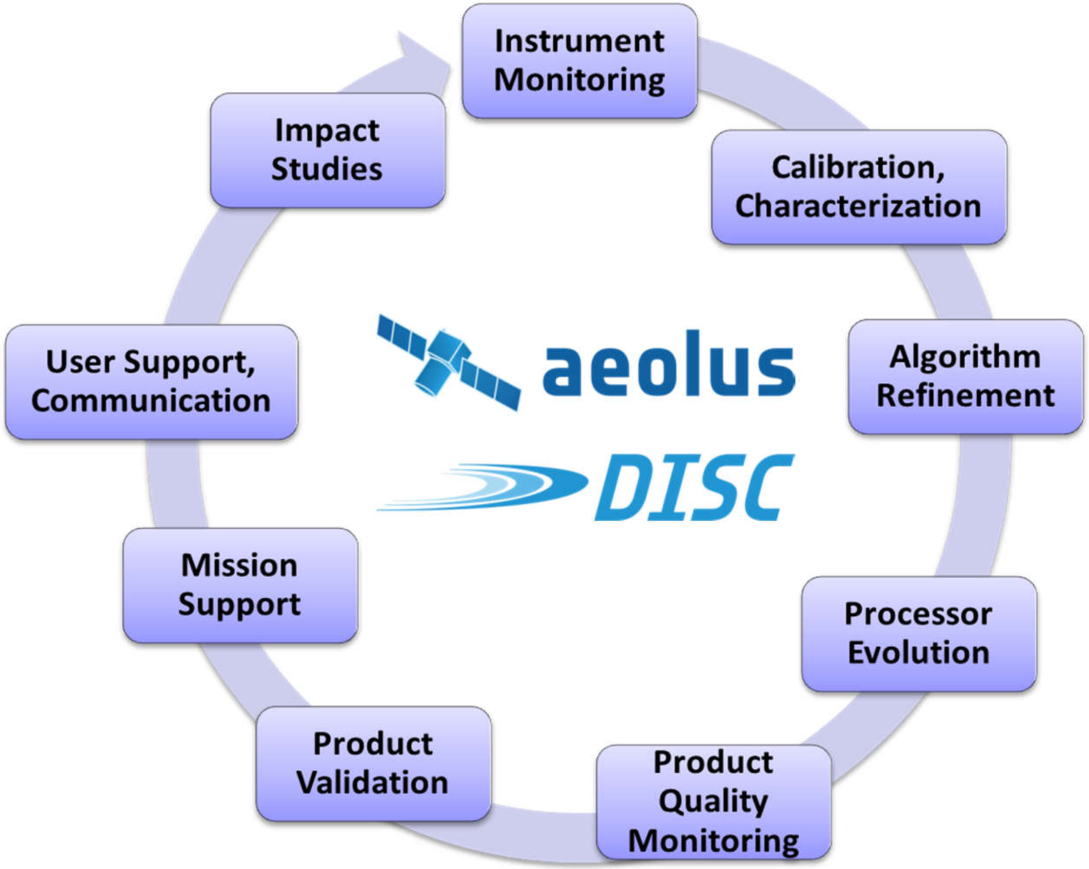
Enhanced dark signals (“hot pixel”) cause systematic errors of ±(1-3 m/s) for Rayleigh winds for some range gates
=> horizontal stripes

June 14, 2019

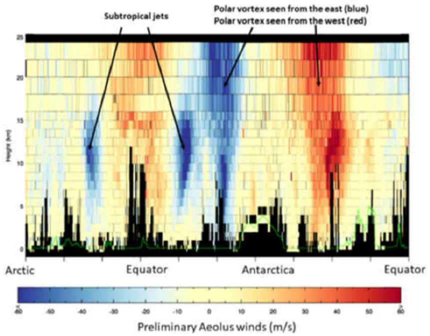
Correction of dark signals in operational L1 processing using specific instrument mode to measure dark signals 4 times per day for real-time datasets

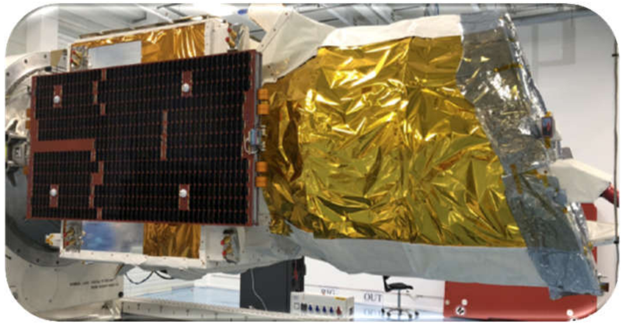
Fig. ViRES for Aeolus; correction developed by F. Weiler (DLR) and D. Huber (DoRIT)

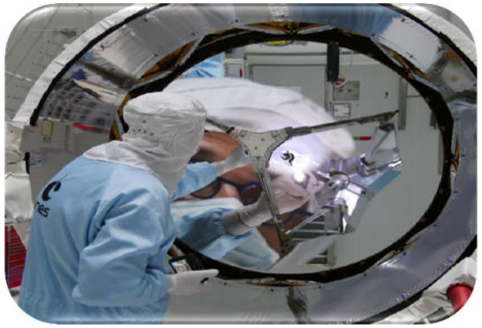
The Aeolus Data Innovation and Science Cluster DISC

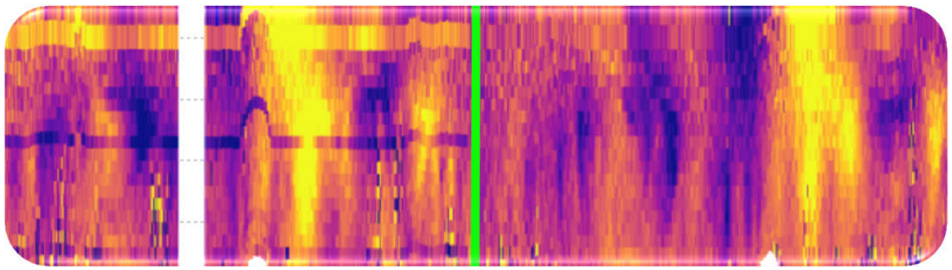


DLR
DoRIT
ECMWF
METEO FRANCE
Toujours un temps d'avance
ABB
Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu
serco
s[&]t
esa
Physics Solutions
OLA
IB Reissig



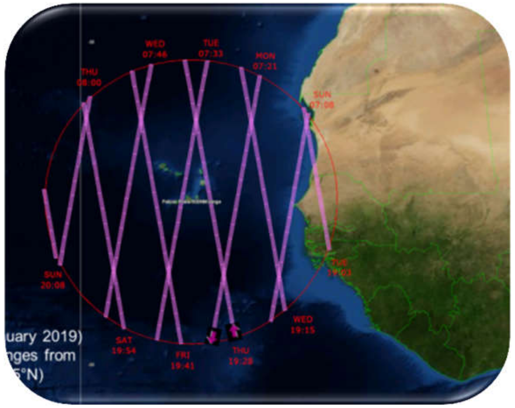


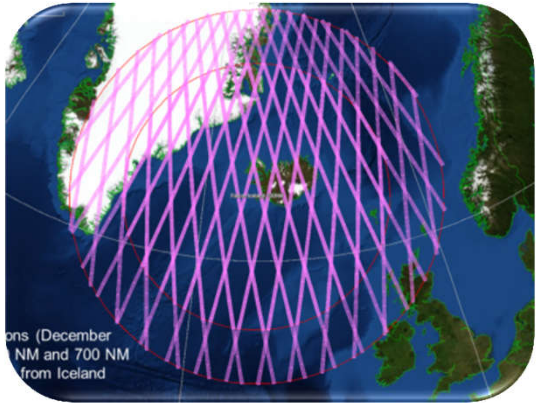


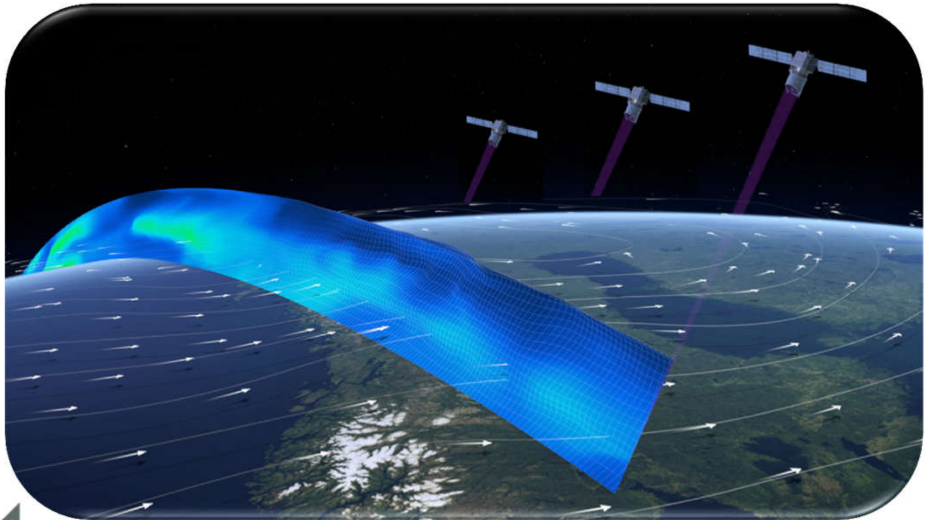


Summary and Conclusion

- From lidar perspective it was demonstrated that:
  - a **space-borne wind lidar can measure atmospheric winds** by use of molecular Rayleigh and cloud Mie backscatter
  - a **powerful UV laser can be operated in space** with high frequency stability
- One objective **of successful technical proof** for Earth Explorer mission is achieved
- The **Rayleigh wind random errors are higher** than expected due to lower signal levels caused by lower laser energy and signal loss in optical receive path
- The **systematic error is currently higher** than required, but precise instrument characterization and use of ground returns will **allow bias corrections;** "hot" pixel correction was recently implemented for real-time data stream







Outlook

- **#1 priority: bias correction** and re-processed dataset for impact studies, instrument characterization and calibration **after switch-on of 2nd laser on June 26, 2019**

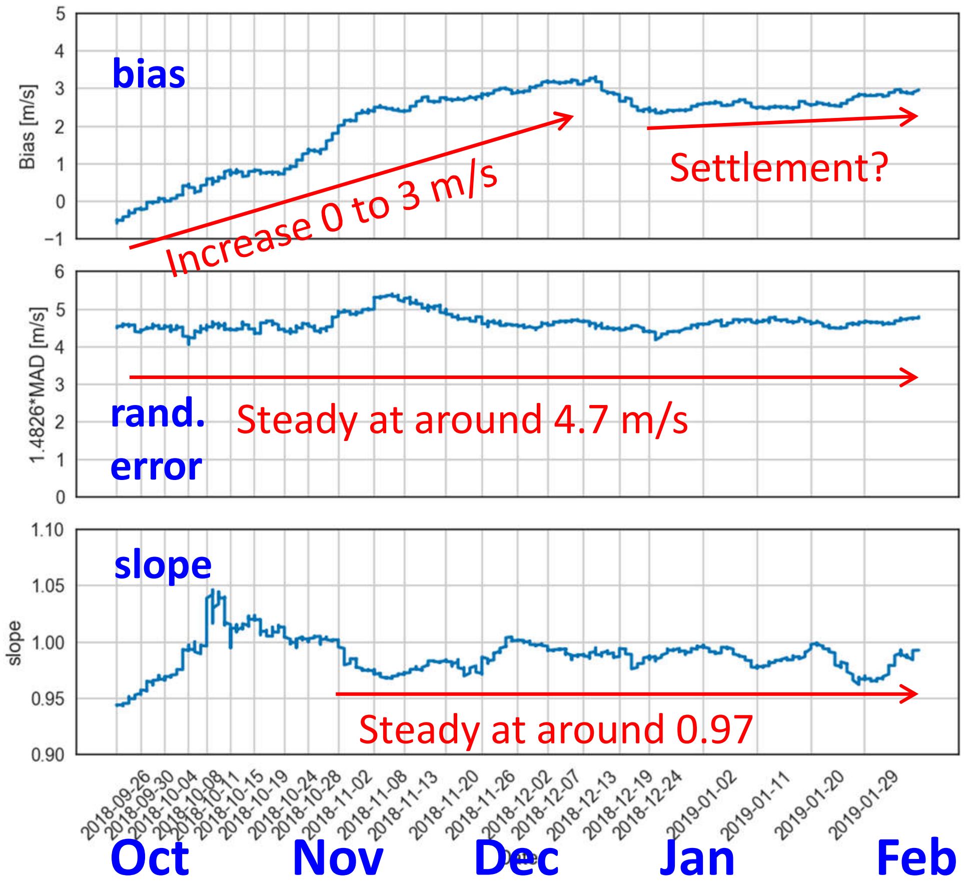
➢ Airborne validation campaigns are planned September 2019 (Iceland), and June 2019 (Cape Verde) with ground-based lidars and wind-lidars/-radars on DLR Falcon, French Falcon and possibly NASA DC-8

➢ Aeolus follow-on missions are discussed in Europe (EUMETSAT, ESA), but need international collaboration to realize 3 wind lidars in orbit (Marseille et al 2008, Tellus) to close gap for winds in WMO global observing system

DLR

Temporal evolution of Aeolus bias and random error

Rayleigh clear



Mie cloudy

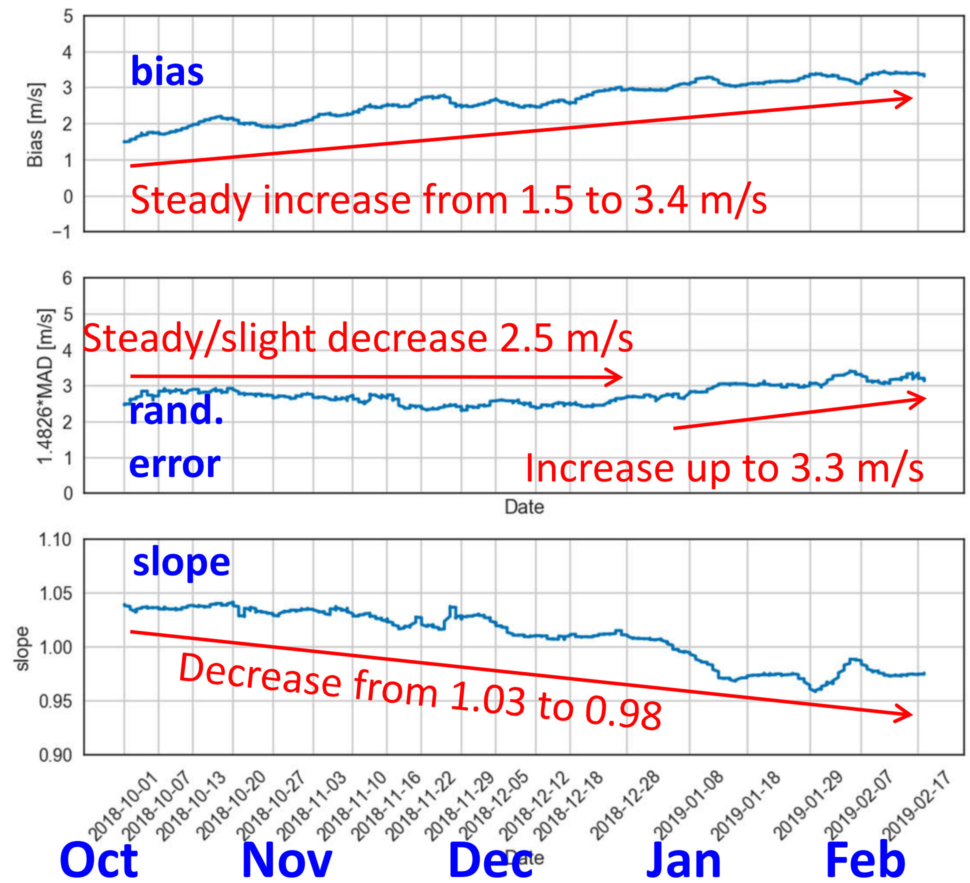


Fig. A. Geiss (LMU)