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Upgrading an End-to-End Simulator for Aeolus to EPS-Aeolus

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The Aeolus mission

On **August 22nd, 2018**, the European Space Agency (**ESA**) **launched** its Earth Explorer satellite **Aeolus**, which carried a **wind lidar** into space for the **first time**. It emitted laser pulses at 355 nm and analysed the light, that was Doppler shifted and backscattered by the atmosphere. During its almost **five years of operation** Aeolus provided the first measurements of line-of-sight **wind profiles** between 0 – 30 km on a global scale and in near real time, which showed a significantly and **positive impact on numerical weather prediction**. On July 28th, 2023, ESA successfully performed an **assisted re-entry** of Aeolus, another **world's first**.

The objective of the Aeolus mission was to improve numerical weather prediction (NWP) and advance our understanding of atmospheric dynamics and climate processes by considering the obtained wind measurements. The associated Doppler frequency shifts of cloud/aerosol and molecular backscatter were derived from two complementary receiver channels (Mie and Rayleigh), each employing an accumulation charge-coupled device (ACCD).

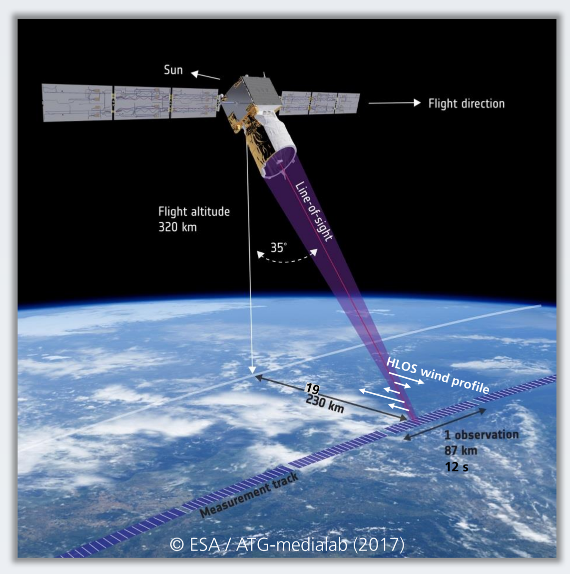
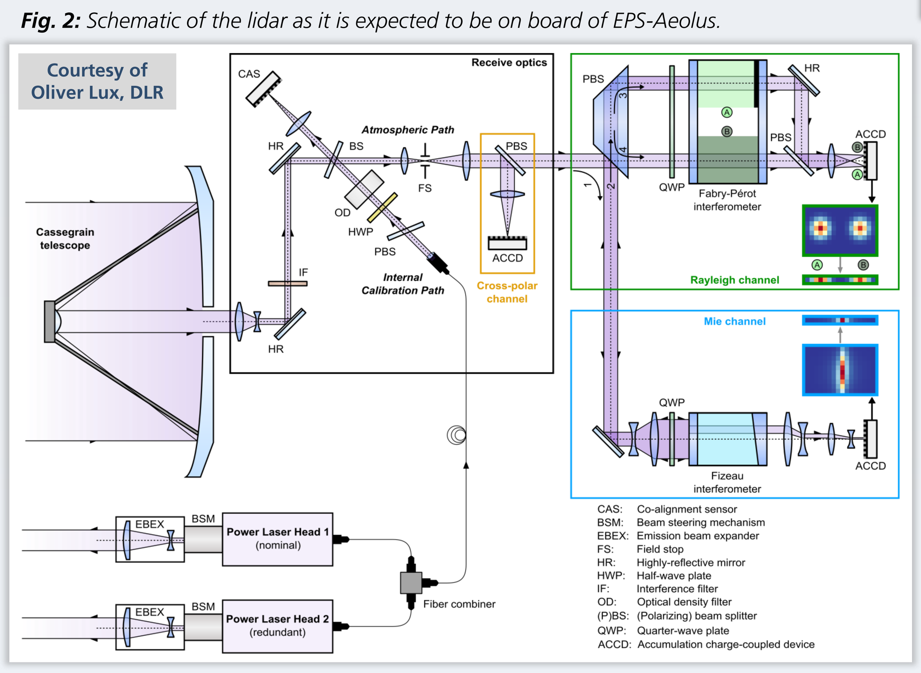


Fig. 1: Viewing geometry and sampling strategy of the Aeolus satellite for horizontal line-of-sight (LOS) wind speed (adapted).

Fig. 2: Schematic of the lidar as it is expected to be on board of EPS-Aeolus.

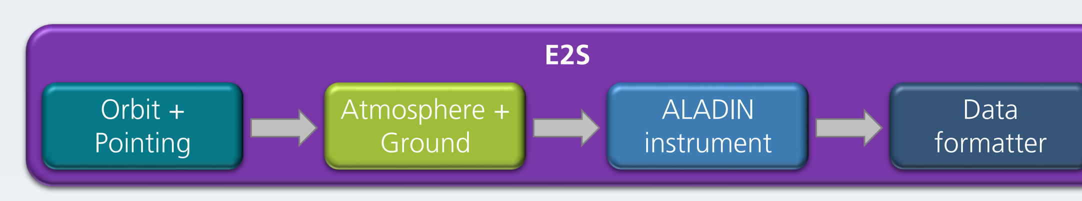


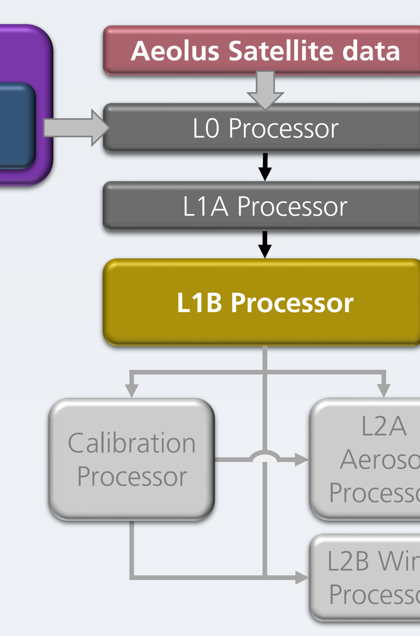
Starting with the launch of the first of two satellites in 2034, **EPS-Aeolus** will be an **operational** mission with the aim to provide more data of higher quality and more timely. Therefore, the new lidar instruments are planned as a **bi-static** setup (Aeolus = transceiver), which requires active controlling of the alignment of laser and telescope. New **ACCDs** will allow for higher vertical resolution of the wind profiles, and an additional channel for **cross-polarized light** shall improve the aerosol and cloud classification.

The Aeolus End-to-End Simulator (E2S)

Based on the success of Aeolus, the follow-on mission **EPS-Aeolus** (Aeolus-2 for ESA) is planned in cooperation between EUMETSAT and ESA. We reconfigured the existing **Aeolus End-to-End Simulator** (E2S) to evaluate the **radiometric performance** of the Aeolus **Rayleigh** channel by comparing simulated and measured signals, as well as to representatively simulate the planned **mission performance** of EPS-Aeolus. Our investigations are based on Level 1B data, i.e. on spectrometer data and wind profiles at measurement and observation scale derived by using algorithms that do neither consider scene classification nor a correction for pressure/temperature effects.

By considering the detailed technical characteristics of the instrument as well as **user-defined** atmospheric conditions, the E2S produces Rayleigh and Mie signal data. Together with albedo and Digital Elevation Model (DEM) information as well as housekeeping and ephemeris data, the **E2S** then creates **output** files with the same **format as** provided by the **Aeolus satellite**. 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. **After launch**, the E2S was for example used for estimation of initial signal loss.





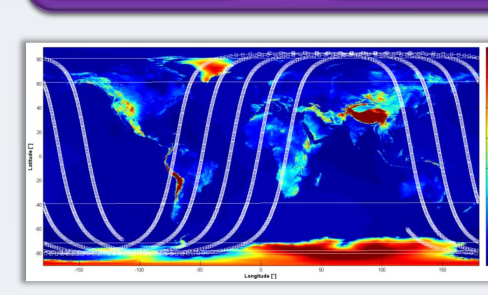


Fig. 3: Map of the ACE-2 DEM and ground tracks of 5 consecutive orbits of Aeolus.

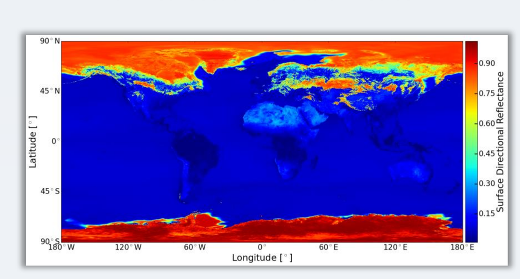


Fig. 4: Adapted map of UV surface albedo based on ESA's ADAM database v.3.0.

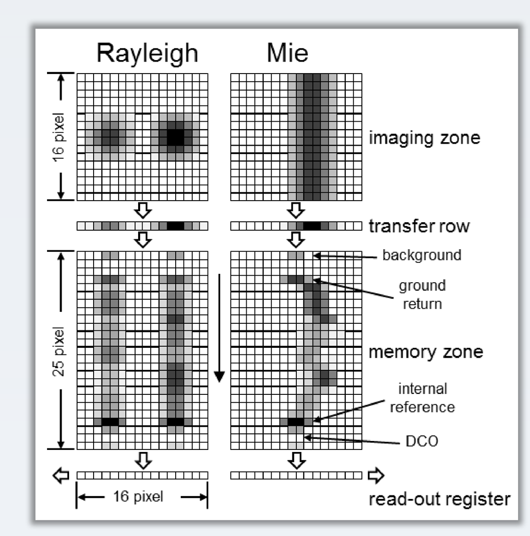


Fig. 5: Simplified operation principle of Aeolus' ACCD detectors.

Fig. 6: Schematic of the Aeolus processing chain with detailed sequence for the E2S. This study used the E2S and L1B of Baseline 16. The L2A and L2B processors were not used.

Updates of the E2S configuration in view of EPS-Aeolus

Table 1: *Wind precision requirements for EPS-Aeolus (R. Chalex, EUMETSAT, 2024).*

Rayleigh Wind Profile		Horizontal Resolution	Vertical Resolution (Threshold)	Vertical Resolution (Breakthrough)	Precision (RMS)
Planetary Boundary Layer	(0 – 2 km)	100 km	-	-	5.0 m/s
Troposphere	(2 – 16 km)	100 km	1.0 km	0.50 km	2.5 m/s
Stratosphere	(16 – 30 km)	200 km	2.0 km	1.00 km	5.0 m/s
Mie Wind Profile					
Planetary Boundary Layer	(0 – 2 km)	10 km	0.5 km	0.25 km	2.0 m/s
Troposphere	(2 – 16 km)	10 km	1.0 km	0.50 km	2.5 m/s
Stratosphere	(16 – 30 km)	200 km	2.0 km	1.00 km	5.0 m/s

- As a first step, **E2S parameters** (*such as optics transmissions, laser energy and noise sources*) were **adapted** to obtain backscattered molecular **signals** and **wind random errors** that **match** those observed from real **Aeolus measurements**.
- Second, simulations of **EPS-Aeolus** were performed considering **differences** with respect to **Aeolus** mainly in terms of orbit related parameters, range bin settings, laser energy, solar background and individual calibration files. Rayleigh **wind random errors** were compared to the new **requirements**.
- **8 sections** were selected to reflect all **major periods** of the **Aeolus mission** (*laser A and B / low, medium and high laser energy*). To cover the atmospheric variability, the mostly cloud-free (→ *Rayleigh*) sections exhibit very weak and very strong horizontal and vertical wind gradients and a large range of wind speeds.

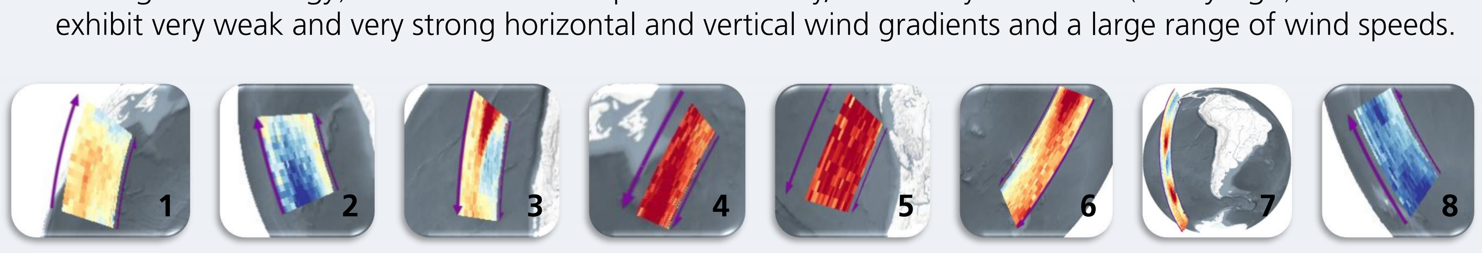


Fig. 7: 8 scenarios as measured by Aeolus between 2018-09-22 (1) and 2023-04-30 (8) and selected for simulation and comparison.

Recent upgrades of the End-to-End Simulator

New: Orbit

- Relevant parameters provided by EUMETSAT for 5 different EPS-Aeolus orbits, including the average altitude above the Earth ellipsoid between 415 km – 485 km.
- Used as input to ESA's EO-CFI

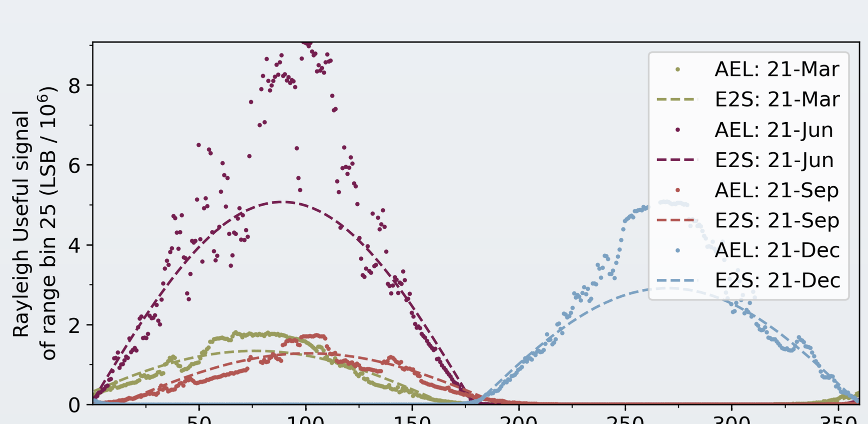


Fig. 10: *Solar background signals as observed by Aeolus (dots) and as provided by the End-to-End Simulator (dashed line) using a receiver Field-of-View of 18.1 µrad (Aeolus) in the simulator for 4 different days in 2020. The days are placed close to spring equinox, summer solstice, autumn equinox and winter solstice to illustrate the different maxima and minima. The North Pole and South Pole are located at 90° and 270° argument of latitude.*

New: Digital Elevation Model

- Switch from ACE-2-DEM with 300 m resolution to Copernicus GLO-90 DEM with 90 m, which is also used in EUMETSATs EPS-SG programme
- Will allow for improved ground detection

New: Bins of 125 m vertical thickness

- As it will be provided as an optional capability by the new ACCD of EPS-Aeolus
- Vertical resolution (under 35° off-nadir) so far only between 2 km & 250 m in steps of 250 m
- Useful for investigation on future improvements of the ground detection algorithm

New: Variable solar zenith angle

- Instead of a fixed solar zenith angle per segment of the simulation, the angle is now available per measurement and with it the solar background signal.
- This enables a better investigation of the impact of the solar background onto EPS-Aeolus observations. The necessary expansion of the Field-of-View will increase the solar background signal and with it the wind random error.

Comparison of E2S simulations to Aeolus and EPS-Aeolus

As a first step, towards an E2S for EPS-Aeolus it is needed to achieve **consistency** between **simulation** and **measurement** for **Aeolus** in terms of the atmospheric signal levels and the wind random error.

Almost **no altitude-dependent error** remains in the ratio of the Rayleigh signal from E2S simulation and Aeolus measurements if the actual atmospheric temperature profiles are used as input to the simulations *(Fig.8)*. On observation resolution the **E2S** produces **less variability** in Rayleigh signal than what is observed from **Aeolus measurements**.

According to the lidar-equation, the received **signal scales with** the square root of the **distance** to the target. Consequently, the signal ***S*** received by EPS-Aeolus can be estimated via the ratio of the orbit altitudes (assuming the same off-nadir angle): $\boldsymbol{S_{EPS\text{-}Aeolus}} = S_{Aeolus} \cdot (320\ \text{km} / 465\ \text{km})^2 = \boldsymbol{S_{Aeolus} \cdot 0.47}$. Considering only Poisson noise, the SNR and the errors depend only on $\sqrt{S}$, which allows to estimate the **increase** of the **Rayleigh wind random errors** from Aeolus to EPS-Aeolus to a factor of about (465 km / 320 km) = **1.45.**

By **scaling the bin sizes** (horizontal extent depends on orbit altitude and product definition) to the requirements on horizontal and vertical resolution in the different atmospheric layers, the wind random error of **EPS-Aeolus** like simulations can be compared to the respective wind precision requirements *(Fig.9)*:

$$\frac{std(HLOS)}{\sqrt{\frac{vertical\_resolution}{bin\_thickness}} * \sqrt{\frac{horizontal\_resolution}{bin\_length}}}$$

- user requirements → vert. / horiz. resolution
- integration times → bin_thickness
- orbit altitude → bin_length

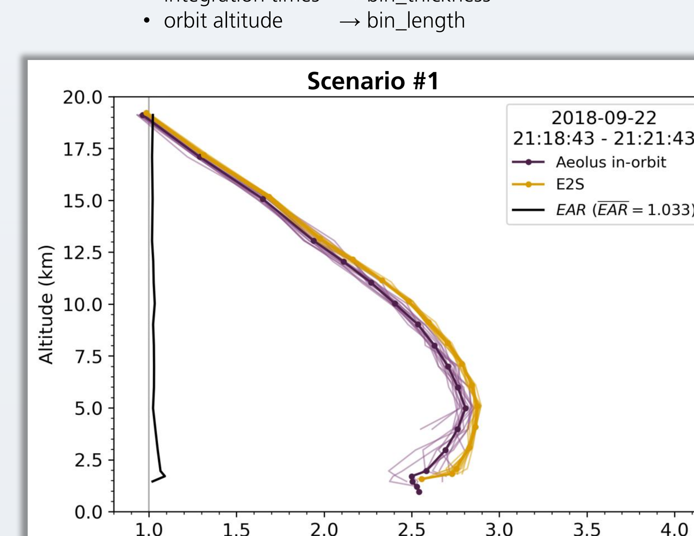


Fig. 8: *Vertical profiles of clear sky valid normalized Rayleigh useful signal from Aeolus measurements (violet) and E2S (orange) as well as the E2S-Aeolus ratio profile (black). Thick lines show the mean values. A realistic atmosphere in terms of pressure, temperature and wind derived from the ECMWF model was considered. A tuning factor was applied according to the signal decay observed during the mission.*

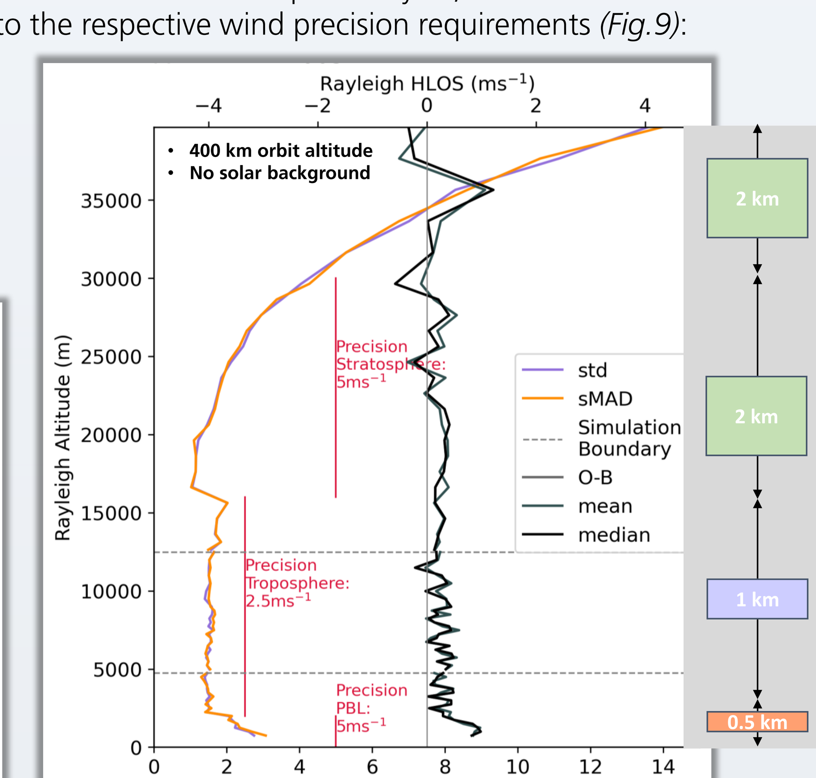


Fig. 9: *L1B Rayleigh HLOS wind bias (black, from comparison against the E2S input wind profile) and random error for EPS-Aeolus simulations (with simplified atmosphere). The user requirements on threshold level (red) are given for the planetary boundary layer (PBL), the troposphere and stratosphere. The random errors are scaled to the corresponding range-gate resolutions (right) of the user requirements.*

Conclusions

- Considering realistic atmosphere and the knowledge about the performance of the Aeolus instrument during operation, the **E2S** is capable of reproducing the **Rayleigh useful signal** profiles of real **Aeolus** measurements with deviations of less than 5%.
- The **E2S** was **updated** such that it can reflect the basic parameters of **EPS-Aeolus** according to the current state of knowledge, including amongst others the higher orbit altitude, the larger number of range-gates, the improved range-gate resolution and the higher laser energy.
- With the current **configuration** of the **E2S** regarding **EPS-Aeolus** the corresponding user threshold **requirements can be met**. However, this result is still based on an orbit altitude of **400 km** (will most likely be: ≈ 465 km), a simplified atmosphere and disregards the impact of an increased solar background.
- **Future improvements** of the E2S should focus on the simulation of, amongst others, the Co-Alignment Sensor, the Beam-Steering Mechanism, the monitoring and characterization of the Rayleigh channel spots, more realistic bias variations along the orbit, the increase of the number of range-gates and a more realistic solar background behaviour.

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