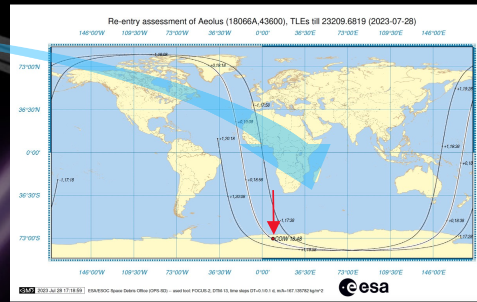
How Aeolus technology development in-orbit performance and lessons learned has shaped Aeolus-2 DWL Instrument and Mission

Space-based 3D Winds Workshop, NCWCP -College Park, MD (US)
19 – 20 Feb 2025

M. Porciani, P. Bravetti, B. Boyes, A. Ciapponi, T. Candra Krisna, D. Wernham

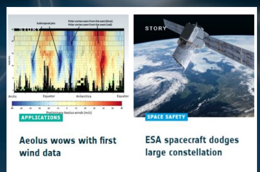
From Aeolus to Aeolus-2

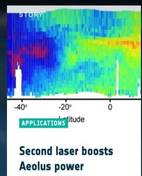
22 August 2018

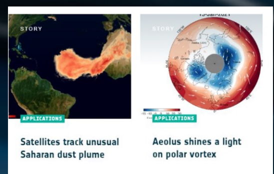


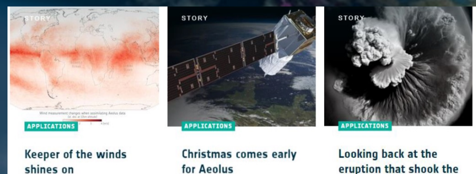
28 July 2023 18:45 UTC

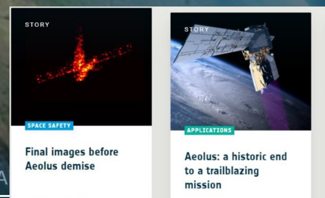
- ✓ 4.5 years of nominal operation (design lifetime 3 years) fuel limited.
- ✓ 3.5 months of intensive-extensive End-of-Life Activities (EOLA)
  a.k.a *Laboratory Activity in Space* [(1)]
- ✓ First <u>assisted re-entry</u> on 28 July 2023 18:45 UTC











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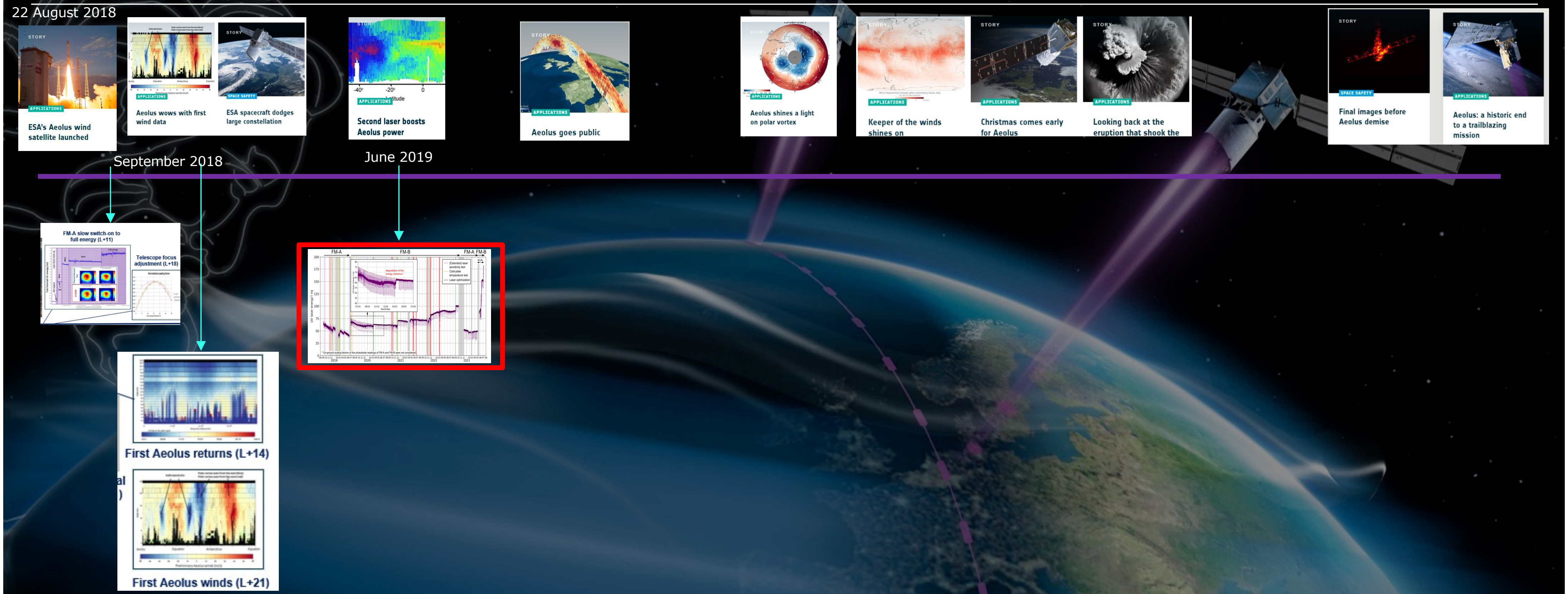
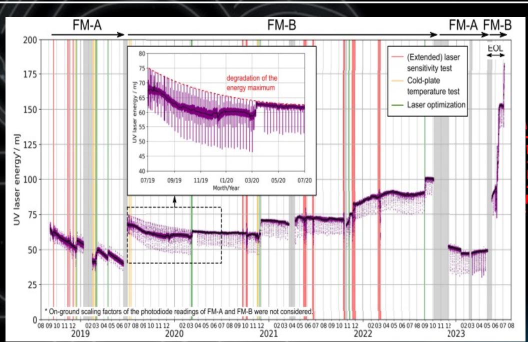
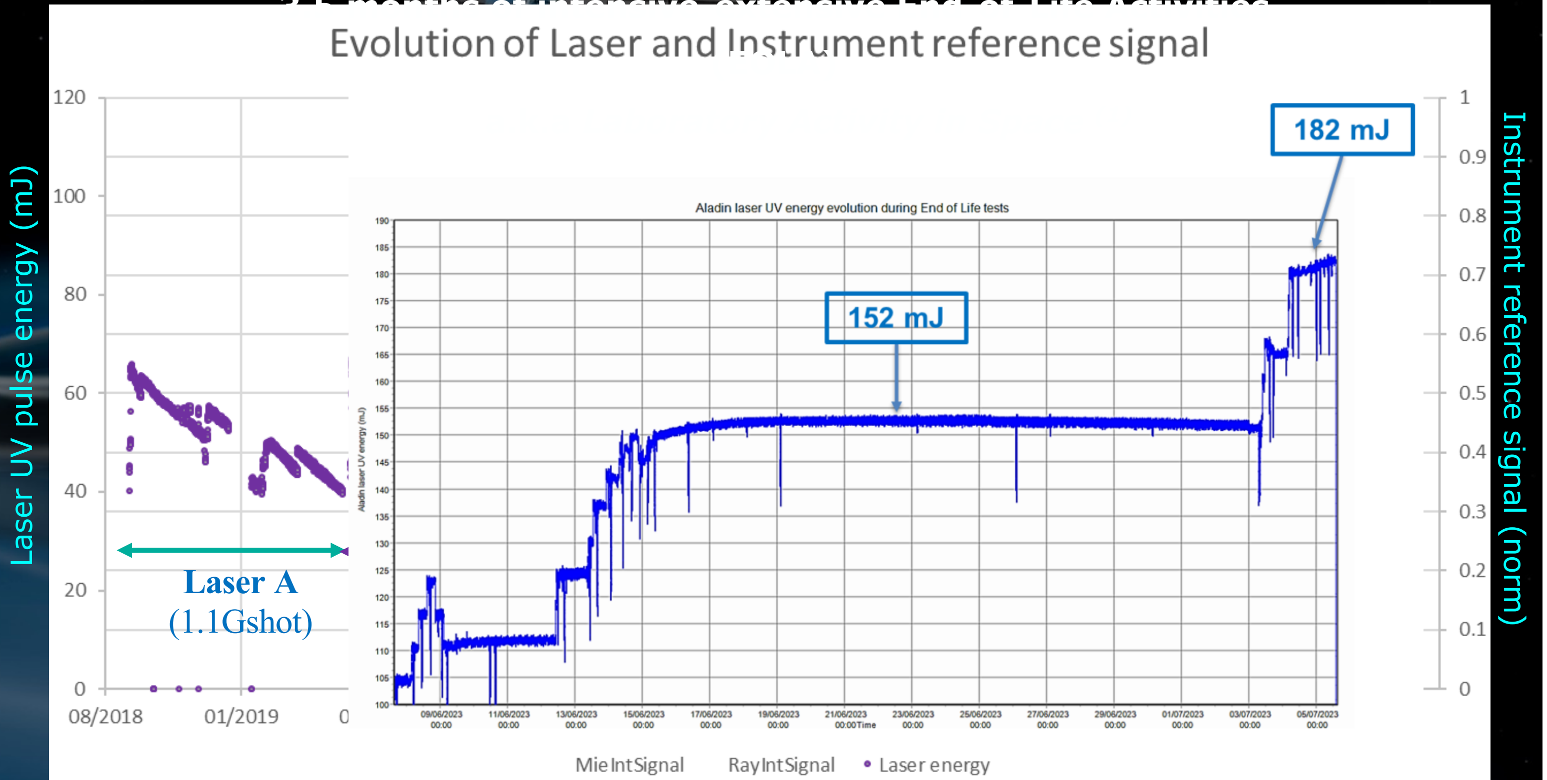


Aeolus laser energy evolution



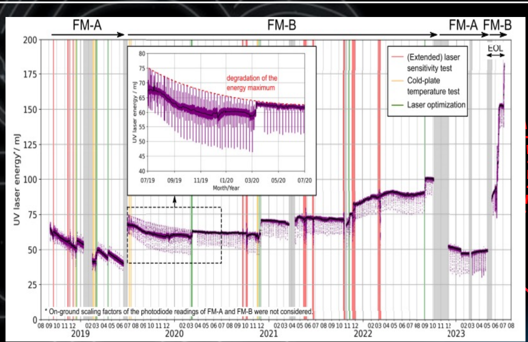
O. Lux et. al., Performance of the ultraviolet laser transmitter during ESA's Doppler wind lidar mission Aeolus, App. Opt. **63**, No. 36 (2024)



Internal laser energy evolution

1. **Laser A operation**, energy reduction due to usage on-ground, slight **misalignment, diode aging** and set point detuning
2. **Laser B** operation: energy roughly constant, several set point variations were implemented to **increase energy** eventually up to more than 100mJ
3. **Laser A** switched back on: energy is constant due to a much better set point tuning

Aeolus laser energy evolution



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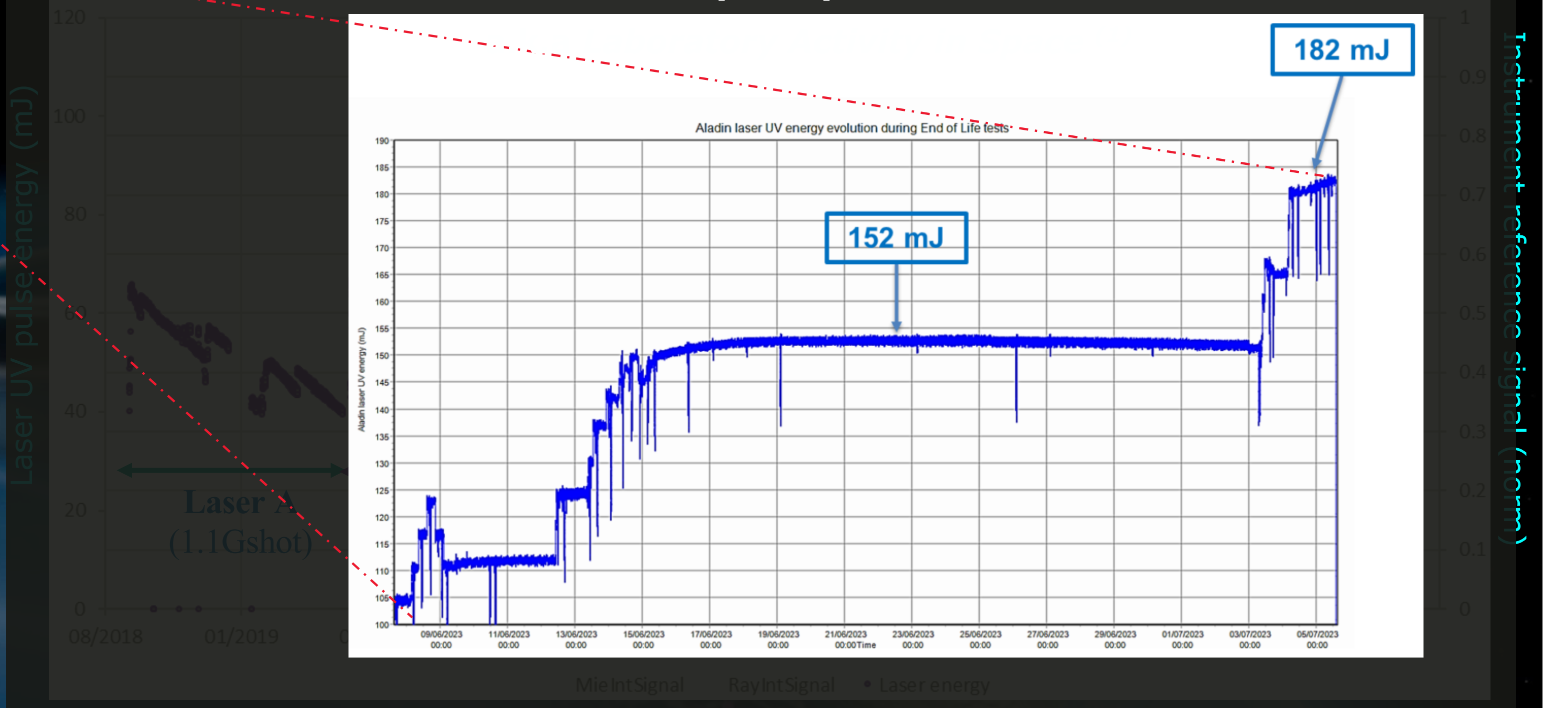
3.5 months of intensive-extensive End-of-Life Activities (EOLA)



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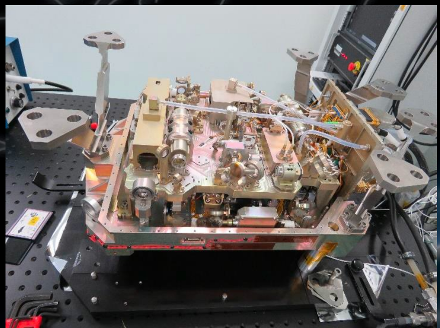
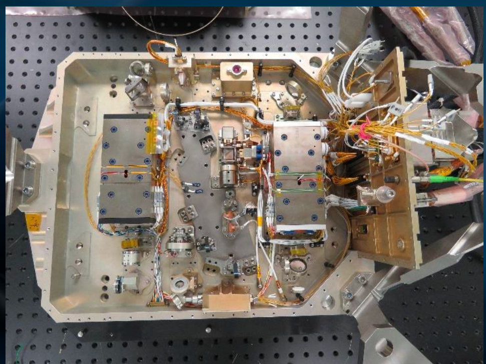
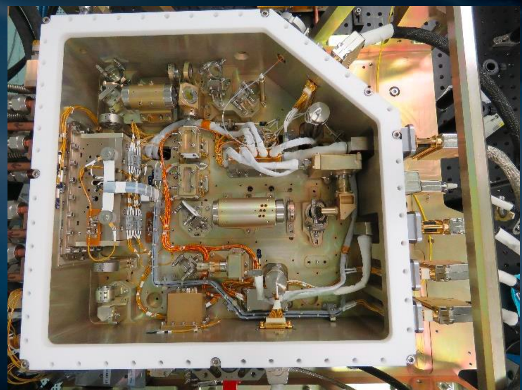
Power Laser Head species evolution

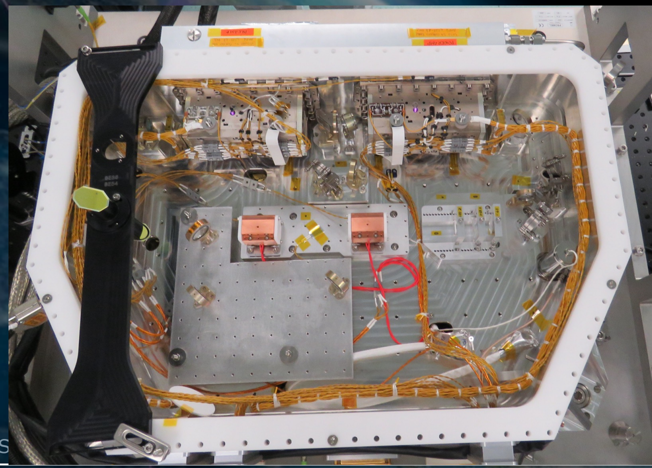




Aeolus / Aladin



EarthCare / Atlid



Aeolus-2

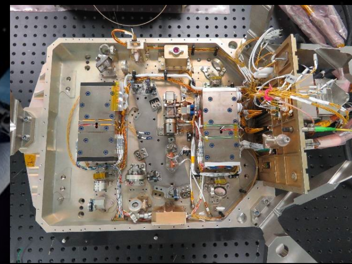
Courtesy of Leonardo (I)

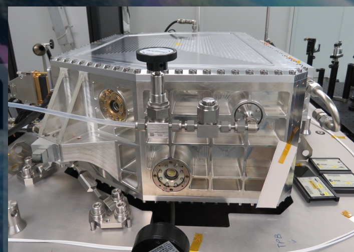
Aeolus-2 Laser Transmitter Assembly

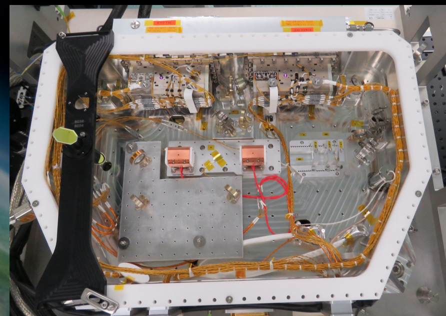
ALADIN, Aeolus' Laser Transmitter, has been *One of the most sophisticated instruments ever put into orbit"* making history, and heritage, for **High Intensity UV Laser in space**

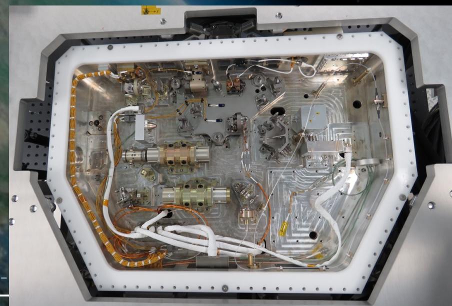
❖ Improved laser design
- More stable laser pointing and Frequency stability
- MO stability and alignment improvement
- Pressurised design
- Increased Output Energy

❖ More challenging laser requirements (to support Instrument bi-static architecture)
- Lower laser divergence
- Larger beam size
- Higher Reliability and Autonomy


Aeolus/ALADIN Laser Head
Courtesy of Leonardo (I)


Aeolus-2 pre-dev Laser Head
Courtesy of Leonardo (I)





Aeolus-2 Laser Transmitter Assembly

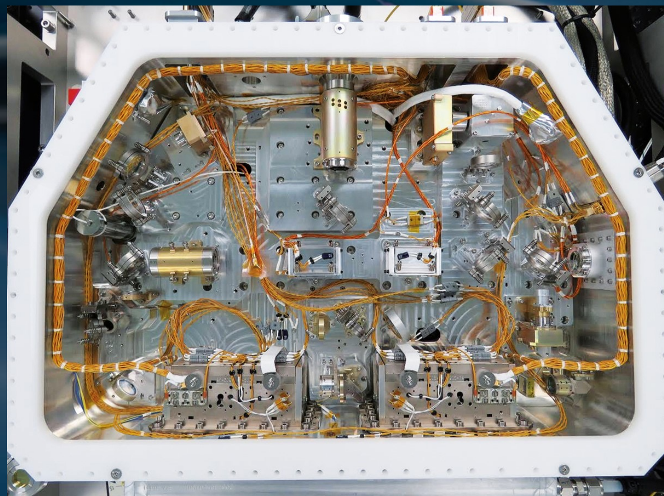
Courtesy of Leonardo (I)

The Aeolus-2 laser transmitter has been designed by Leonardo considering the Aladin and Atlid PLH heritage and lessons learnt.

- Master Oscillator stability improvement due to thermo-mechanical separation with respect to amplification section
- Pressurized structure to avoid air to vacuum transition effects and LIC phenomena
- UV section redesign with enhanced harmonic crystals

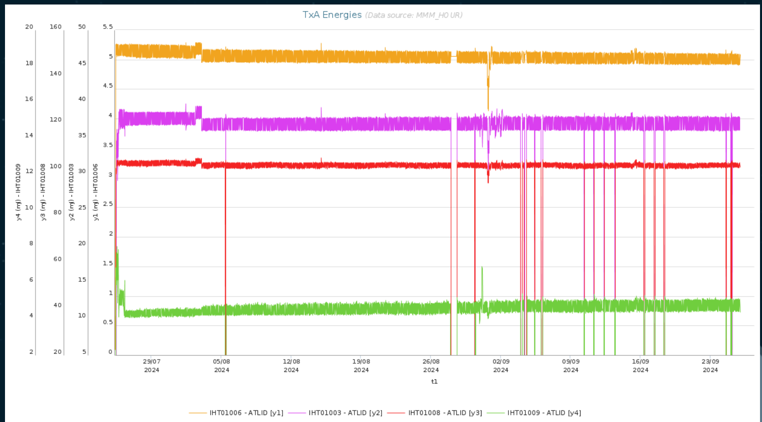
Measured quantities	UV Requirement specification	UV@ UV Window
Pulse Energy (mJ)	>150	161.7
Pixel peak fluence (J/cm^2)	<1.3	0.24
NF $1/e^2$ X (µm)	9000-18000	13980
NF $1/e^2$ Z (µm)		10620
FF Divergence X $1/e^2$ (µrad)	25-75	45
FF Divergence Z $1/e^2$ (µrad)		55
Pulse width (ns)	<100	31.8

Lower Optical Bench
Injection section and Master Oscillator



Upper Optical Bench
Amplification, harmonic and UV sections

ATLID in orbit validation

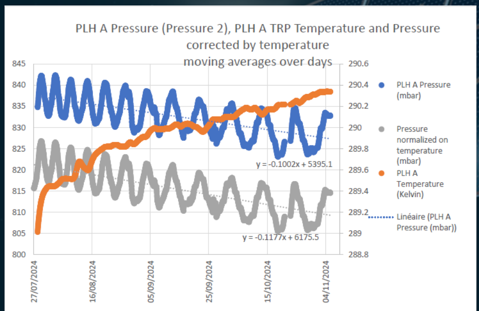


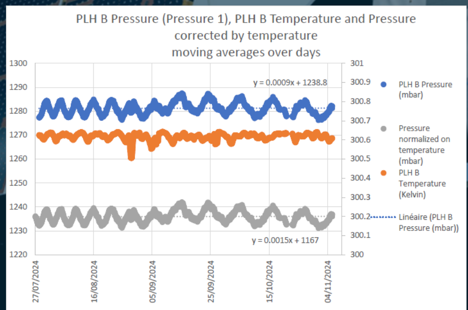
ATLID Laser Energies trend since BOL

- Orange: MO Energy
- Purple: UV Energy
- Red: Amplifier Energy
- Green: Visible Energy

Energy degradation in line with LDs lifetime degradation. First correction expected next summer.

If current trend continues mission lifetime **shall be met with nominal laser with margin**.





PLH A

A loss of 0.1 mbar per day can be observed which is even at 0.12 mbar considering the corresponding temperature evolution

With a minimum authorized pressure of 227 mbar and having started at 840 mbar, this will give a lifetime close to **14 years**.

PLH B

Not possible to detect any measurable leak.

Curtesy of ESA EarthCARE team - JMAG#43 25 Sep 2024 - Status of Atlid Instrument

From Aeolus to Aeolus-2

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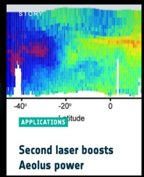
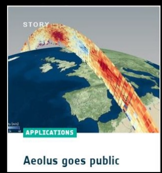
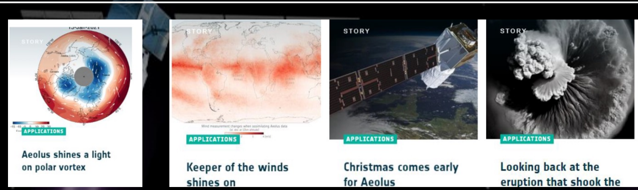
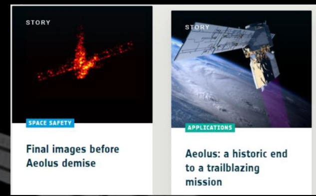




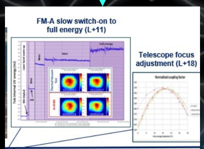


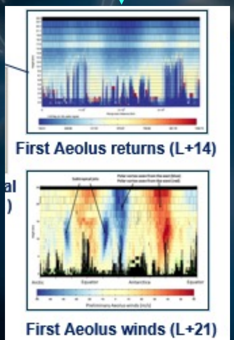


September 2018

June 2019

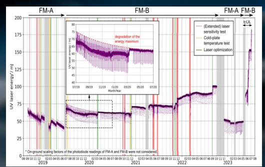
Jan - Jun 2020





First Aeolus returns (L+14)

First Aeolus winds (L+21)



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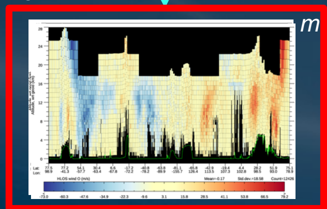
June 2020 assimilation of Aeolus data in Meteo-France and DWD NWP models



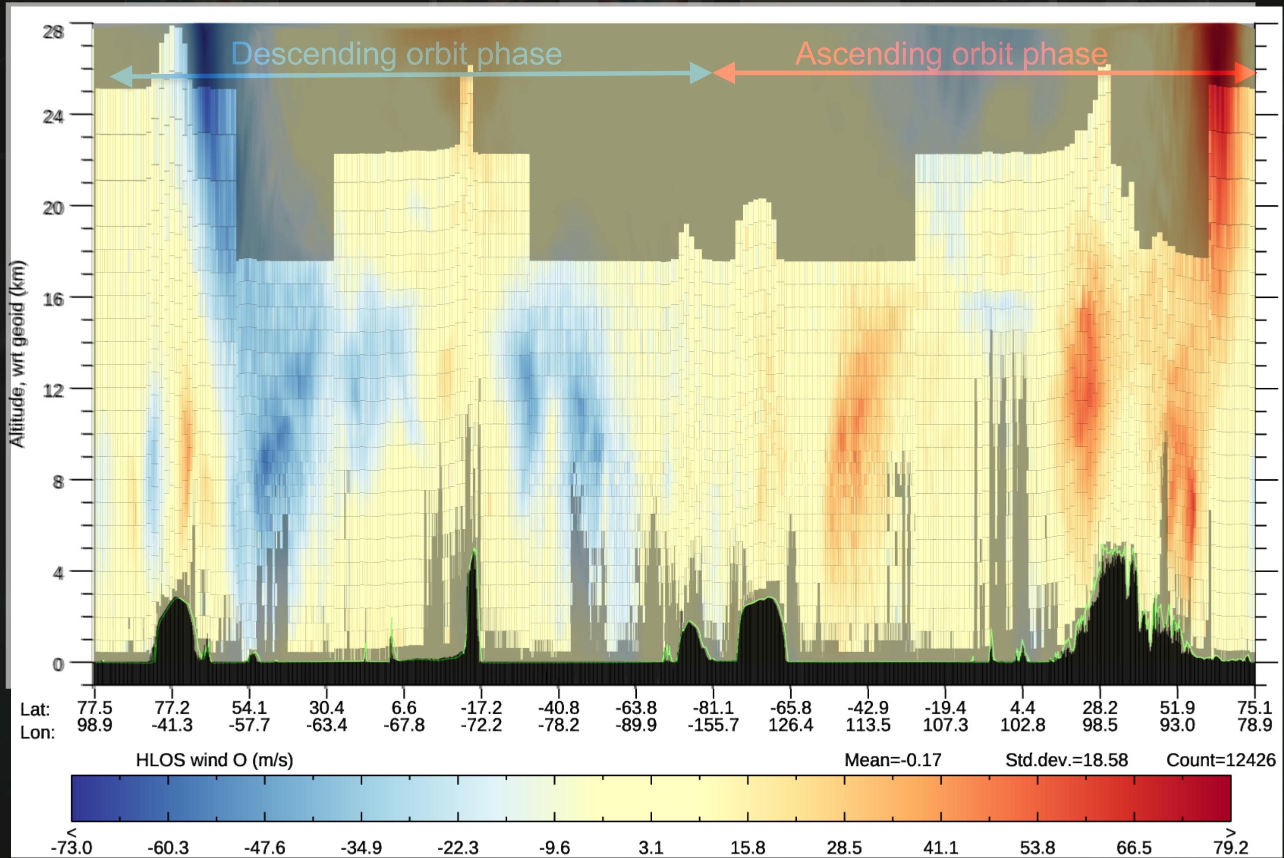
Aeolus Level 2B HLOS winds 10th February 2020 (courtesy Mike Rennie ECMWF).

"And, thanks to all the teams involved and in agreement with EUMETSAT, we are very proud to announce that as of today, Aeolus' data are being distributed in near-real time for numerical weather prediction beyond the Aeolus core user community."

To do this, key Aeolus experts from different organisations worked together in the Data Innovation and Science Cluster team – the Aeolus DISC, to validate and optimise the data processing and bias correction methods."

Early Aeolus wind measurements

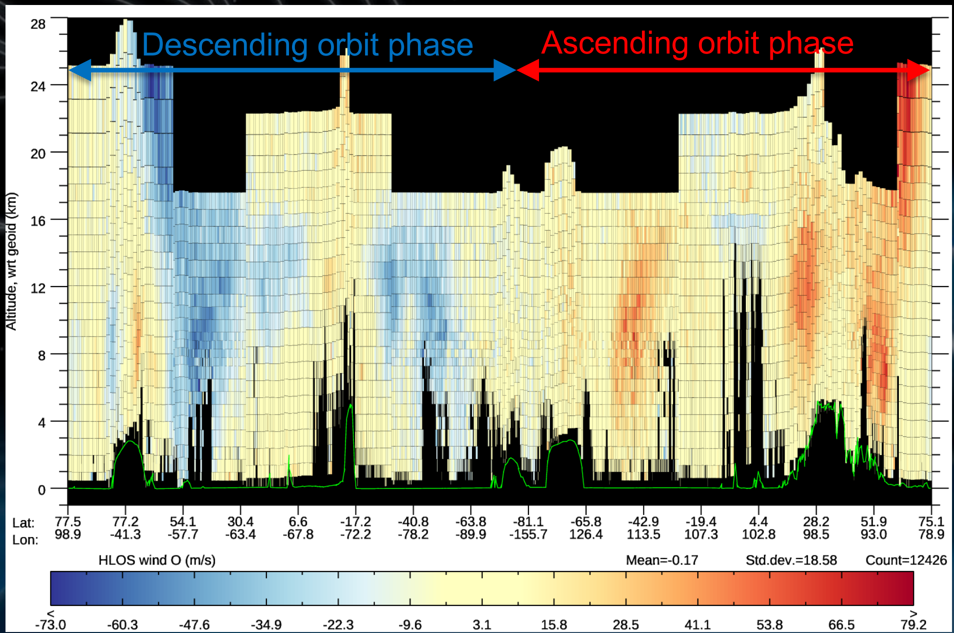
ECMWF forward modelled HLOS winds for the same orbit on 10th February 2020
(Courtesy Mike Rennie ECMWF)



Aeolus Level 2B HLOS winds (Rayleigh Clear + Mie Cloudy) over 1 orbit on 10th February 2020 (courtesy Mike Rennie ECMWF).

(*) Further info in: Rennie and Isaksen (2020), Rennie et al. (2021), Rennie et al. (2022) and the DISC NWP impact ESA Contract Report: Rennie and Isaksen (2024).

Early Aeolus wind measurements



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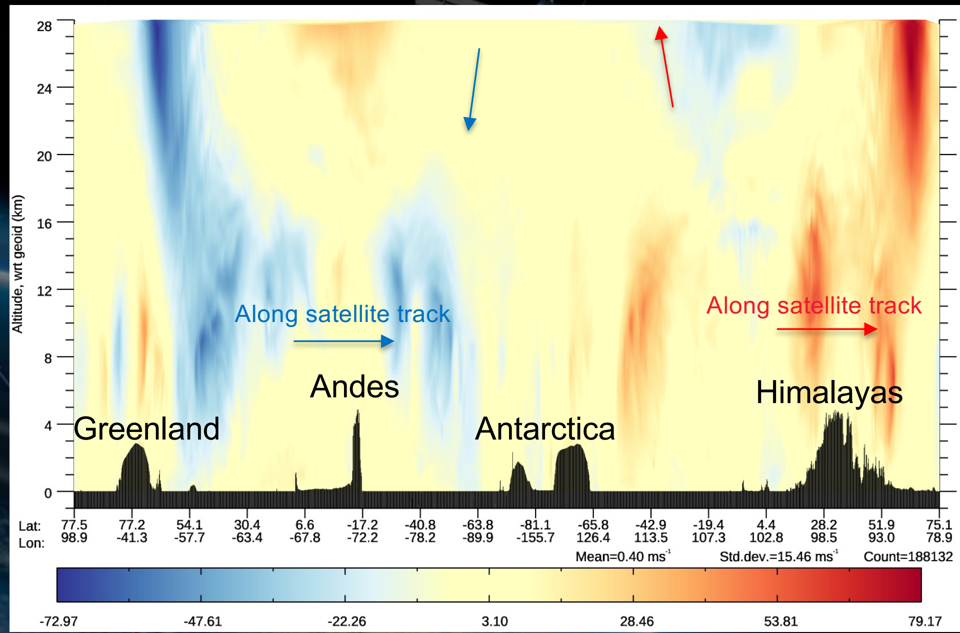
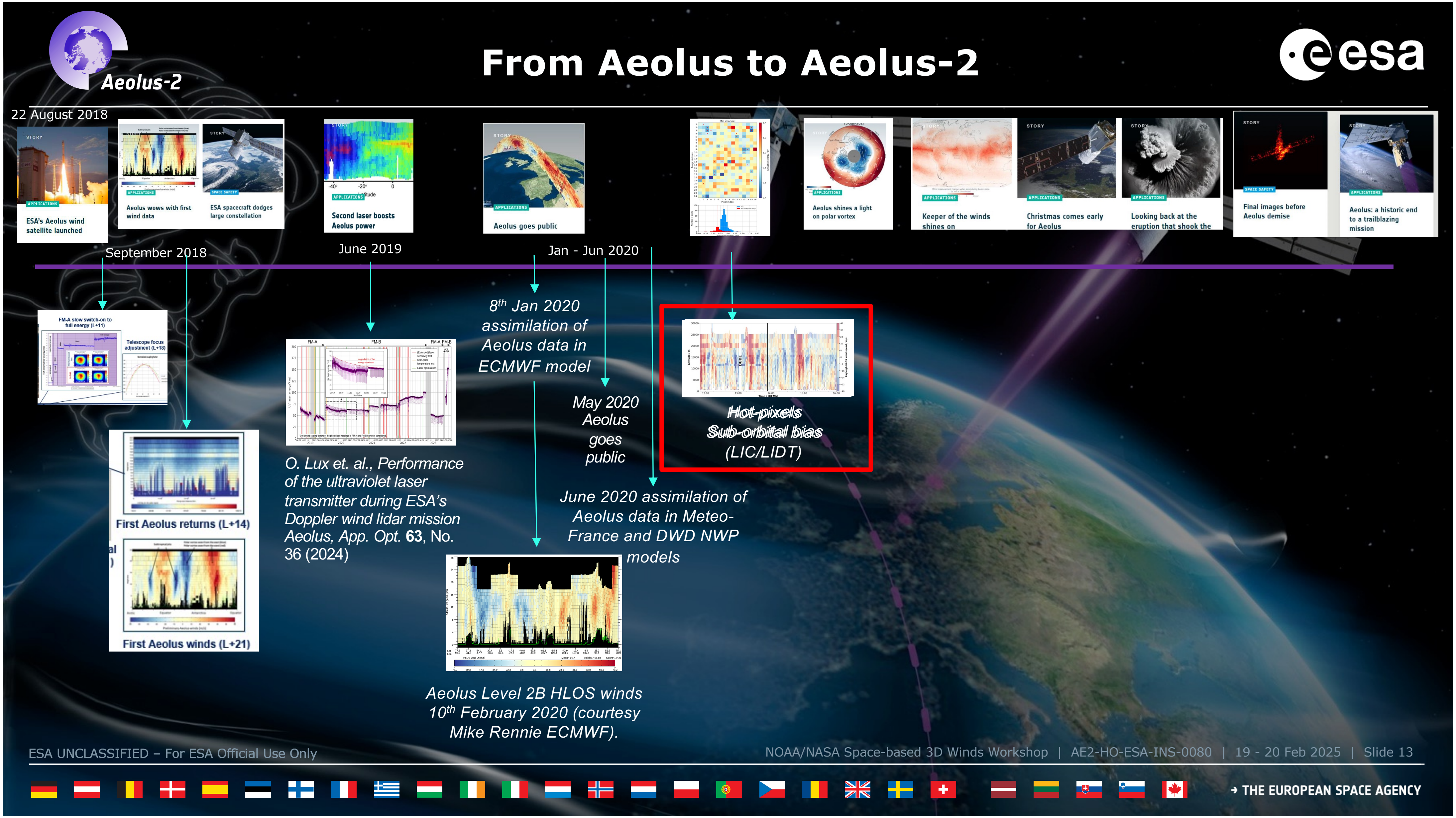


ECMWF forward modelled HLOS winds for the same orbit on 10th February 2020 (Courtesy Mike Rennie ECMWF)

Excellent correlation of the large-scale features between the Aeolus Level 2B measured HLOS winds and the ECMWF modelled winds such as sub-tropical and polar-stratospheric jets.



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Aeolus-2
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Aeolus Level 2B HLOS winds 10th February 2020 (courtesy Mike Rennie ECMWF).
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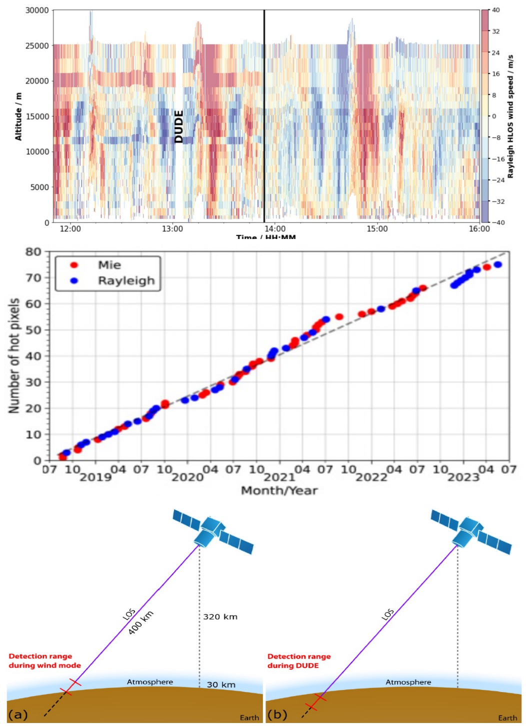
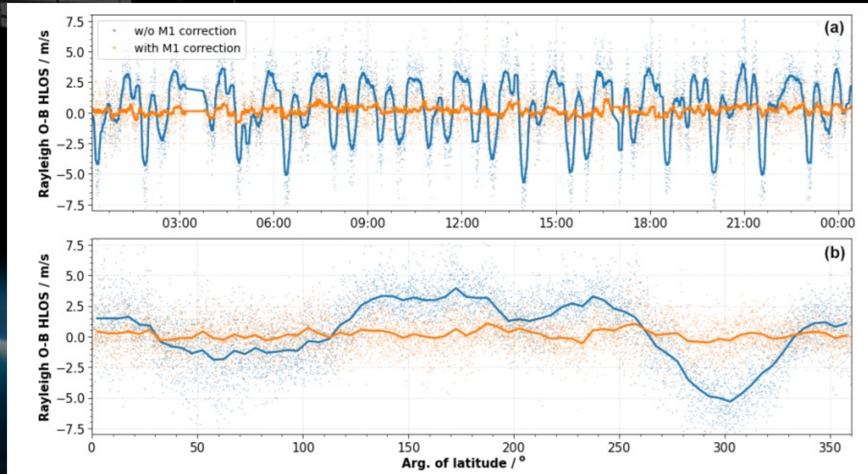
Too large bias



- It became quickly evident that there were "streaks" in the Level 2B product related to certain altitudes which introduced large biases into the wind data.
- This was found to be due to so called "hot pixels" which were pixels that developed slightly higher background noise and had to be cancelled out by a pseudo dark current measurement performed by sending the laser underground (DUDE) in order to correct the background signal.
- The number of hot pixels increased more or less, linearly throughout the mission meaning that the number of DUDEs had to be increased from 4/day to 8/day.
- See: O. Lux et. al. "CCD detector performance of the space-borne Doppler wind lidar ALADIN during the Aeolus mission", App. Opt. **63**, No. 25 / 1 (2024)



- After the "hot pixels" had been fixed, the next issue that arose was a large sub-orbital bias of ± 5ms^{-1}. This was due to the thermo-elastic deformation of the ALADIN primary mirror.
- This was corrected by correlating the mirrors radial thermal gradient with co-located ECMWF wind data.
- This correction was applied by using the previous 12 hours of data to forward correct the next 12 hours which reduced the sub-orbital bias to <1ms^{-1}.
- See: Weiler et. al., "Correction of wind bias for the lidar on board Aeolus using telescope temperatures", Atmos. Meas. Tech., **14**, 7167–7185

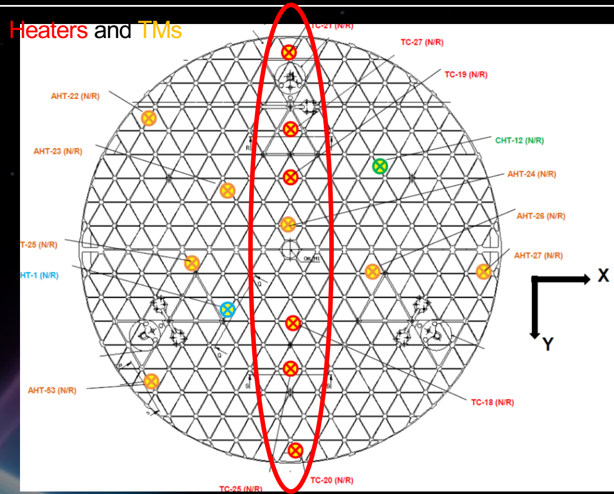
These fixes allowed Aeolus data to be successfully assimilated into NWP models

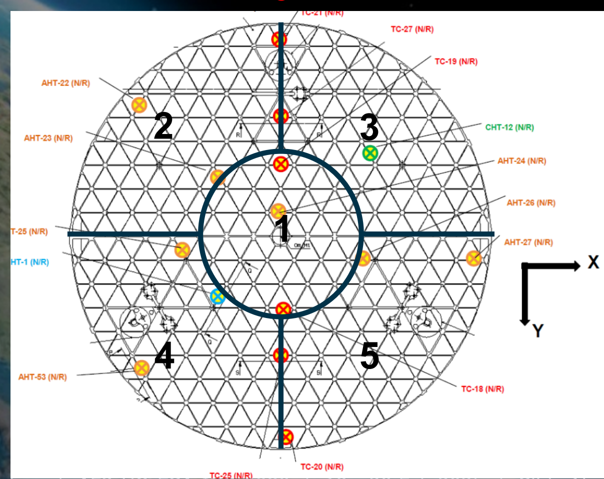
Aeolus-2 ACCD and Mirror

Bias issue

a) Hot pixel → new design for the ACCD and nominal operating temperature lower
b) Dark current will be measured in a regular basis thanks to the design changes (dark current map)

Courtesy of Tel-E2V





Suborbital bias issue (40% signal variation around the orbit)

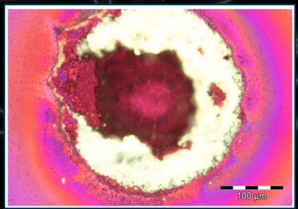
a) Improve of the thermal telescope baffle design (Euclid heritage)
b) Improved thermal design of the M1 mirror, better monitoring and sizing of the thermal control system
c) Struts heating lines are optimized with twice number of lines

Aeolus Super Quality Coating heritage

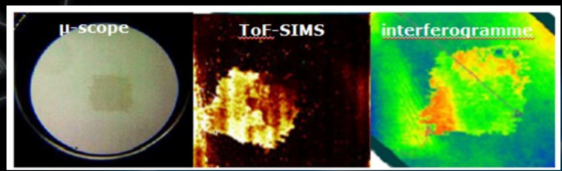
Aeolus-2

esa

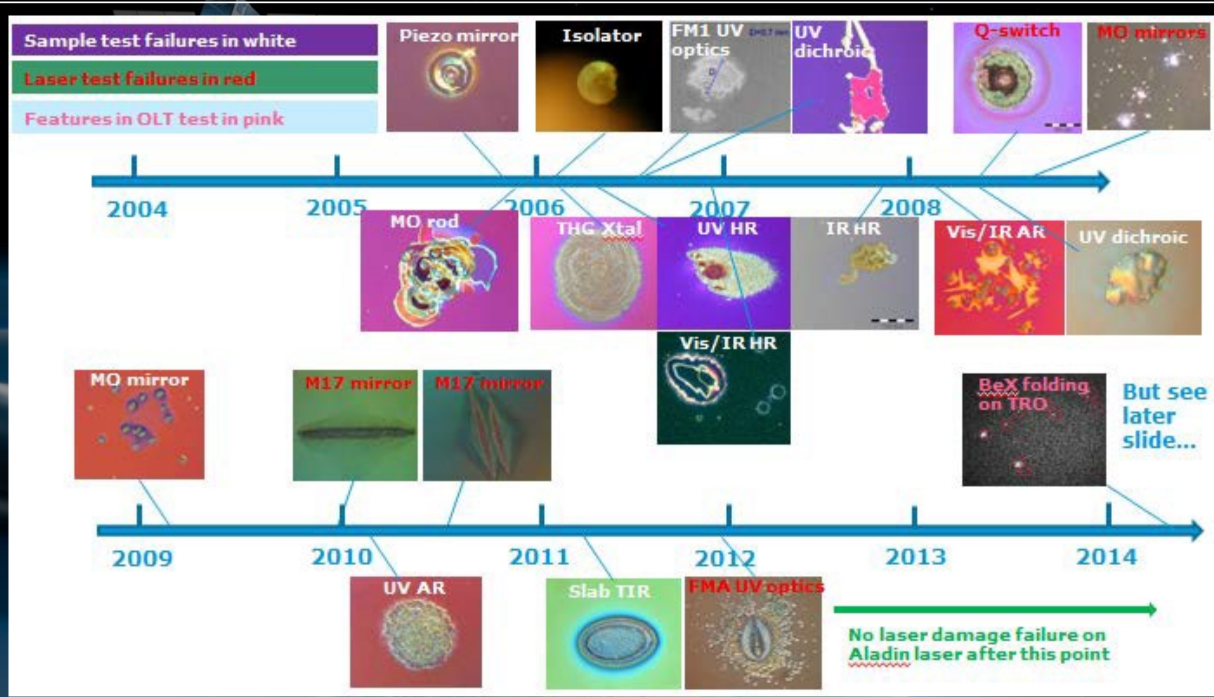
Technology
(development phase)



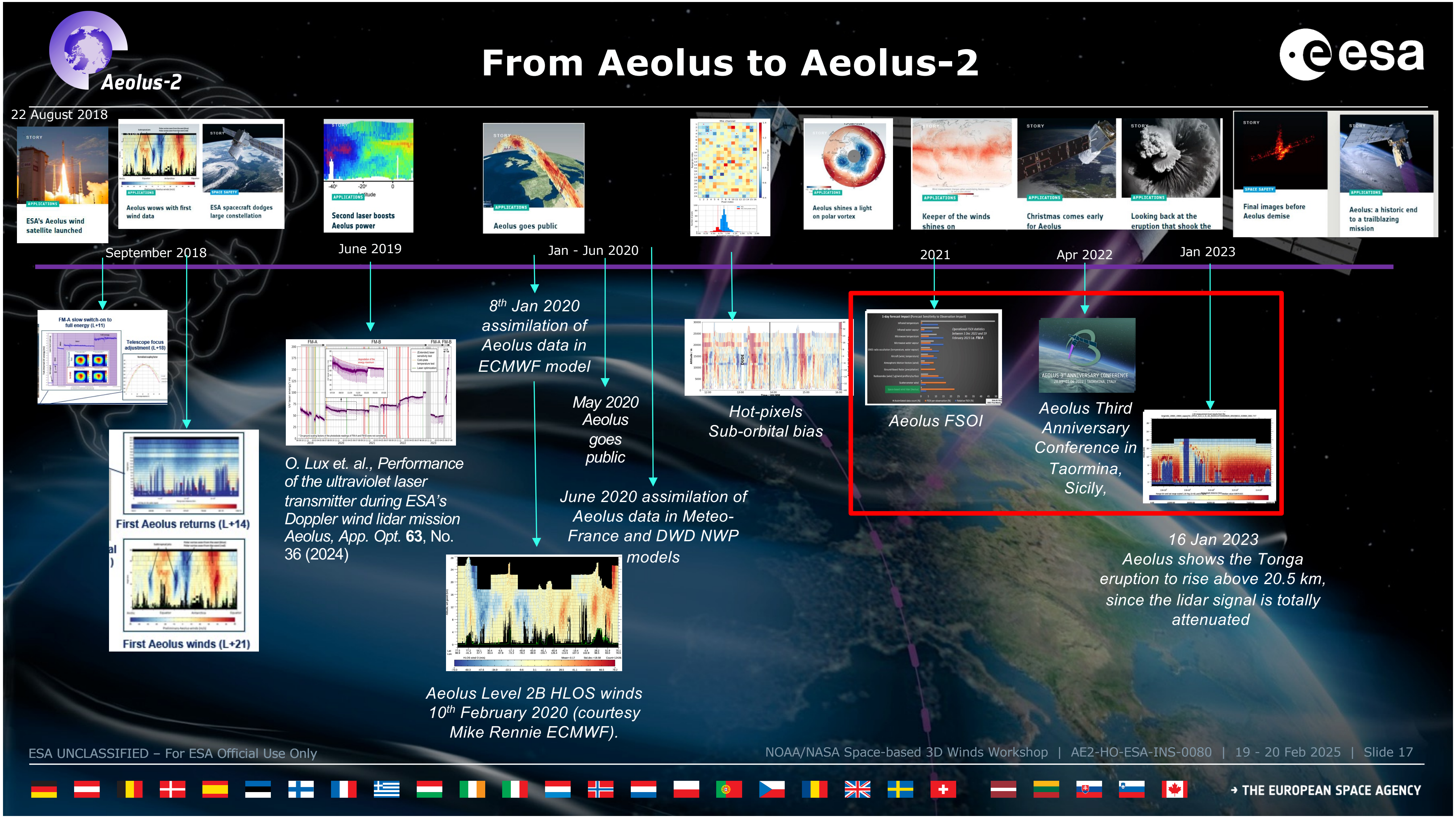
Laser-Induced Damage (LID) to the master oscillator Q-switch resulting in master oscillator failure. Resolved by changing Q-switch coating to one with higher LIDT.



Vacuum test of the PLH EM showed 50% energy degradation in 6 hours. Root cause was Laser-Induced Contamination (LIC). This was solved by running the laser in low pressure oxygen eventually leading to the development of the STRO and the In-situ Cleaning System (ICS).



- ❖ 10 years of technology development for High energy UV laser in space
  - High screened coatings and optics substrates
  - Very rigorous contamination control
  - Use of oxidising environment → Pressurised LTA & Tx path
  - Rigorous selection of materials, to prevent LIC and control LIDT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Hot-pixels
Sub-orbital bias
Aeolus FSOI
Aeolus Third Anniversary Conference in Taormina, Sicily,
16 Jan 2023
Aeolus shows the Tonga eruption to rise above 20.5 km, since the lidar signal is totally attenuated
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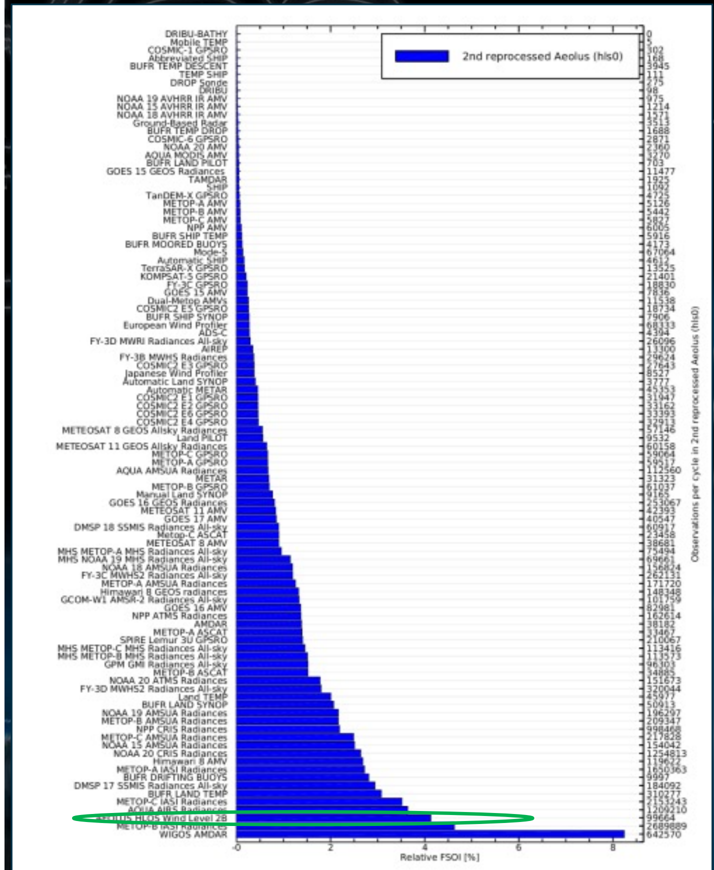
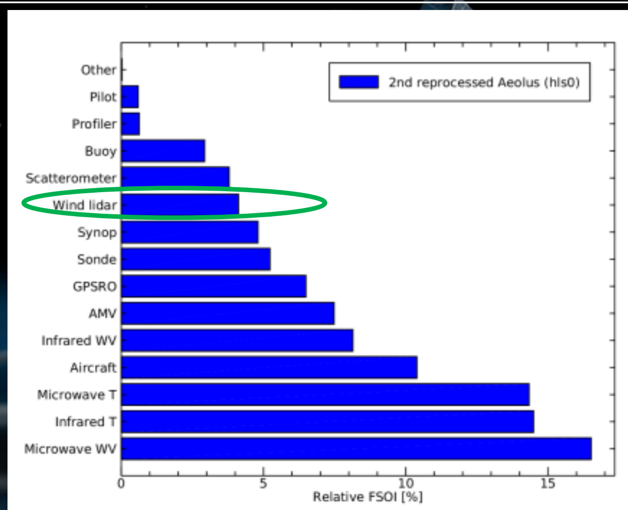
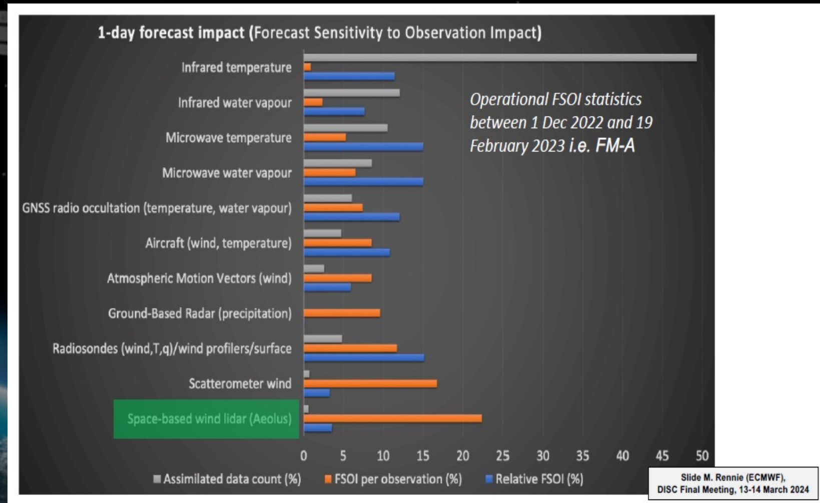
Aeolus' impacts on NWP



Relative FSOI per instrument for FM-B 2nd reprocessed dataset (03/07/2019 – 09/10/2020).



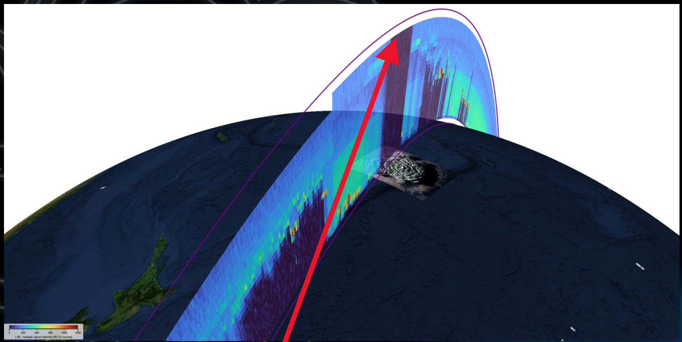


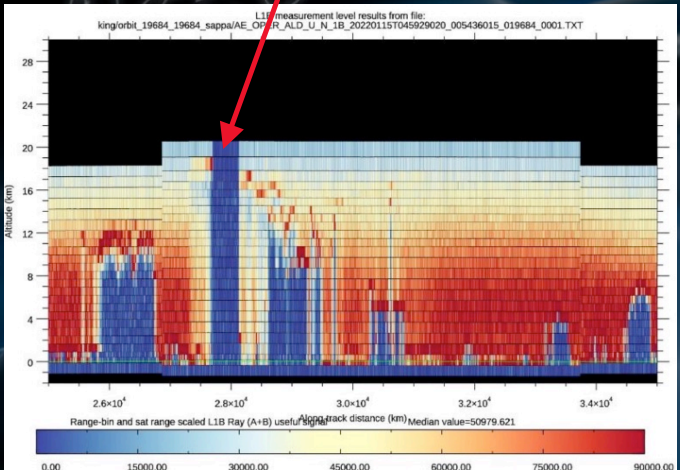
- The relative Forecast Sensitivity to Observation Impact (FSOI) per instrument averaged over the FM-B 2nd reprocessed dataset, from July 2019 to October 2020, indicates that Aeolus was the second most important satellite instrument (after MetOp-B IASI radiances)
- In this period, Aeolus provided slightly more impact than scatterometers and slightly less impact than radiosondes
- This was impressive considering that the initial signal was x2.5 less than expected, and that Aeolus provided <0.5% of the total observations
- This can be seen for the Aeolus data after re-switch on of the FM-A where Aeolus showed the highest 1day forecast impact for any measurement type

Source: The NWP impact of Aeolus Level-2B winds at ECMWF | ECMWF

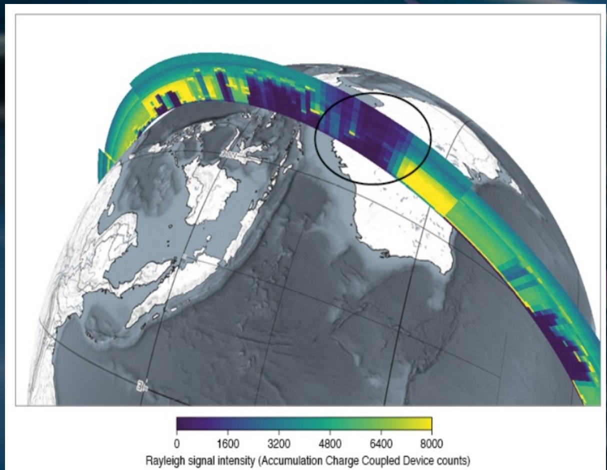
Aeolus' other major impacts

- On 15th January 2022, the Hunga Tonga–Hunga Ha'apai volcano in the southern Pacific Ocean erupted,
- The intensity of the explosion was similar in magnitude to the explosion of Mount Pinatubo in 1991,
- The plume eventually rose to 58 km, beyond the stratosphere and into the mesosphere,
- Aeolus followed the plume as it travelled westwards and widened over Australia

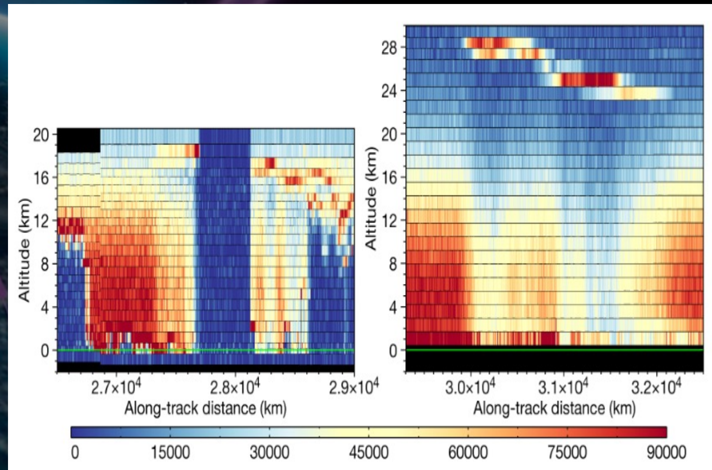




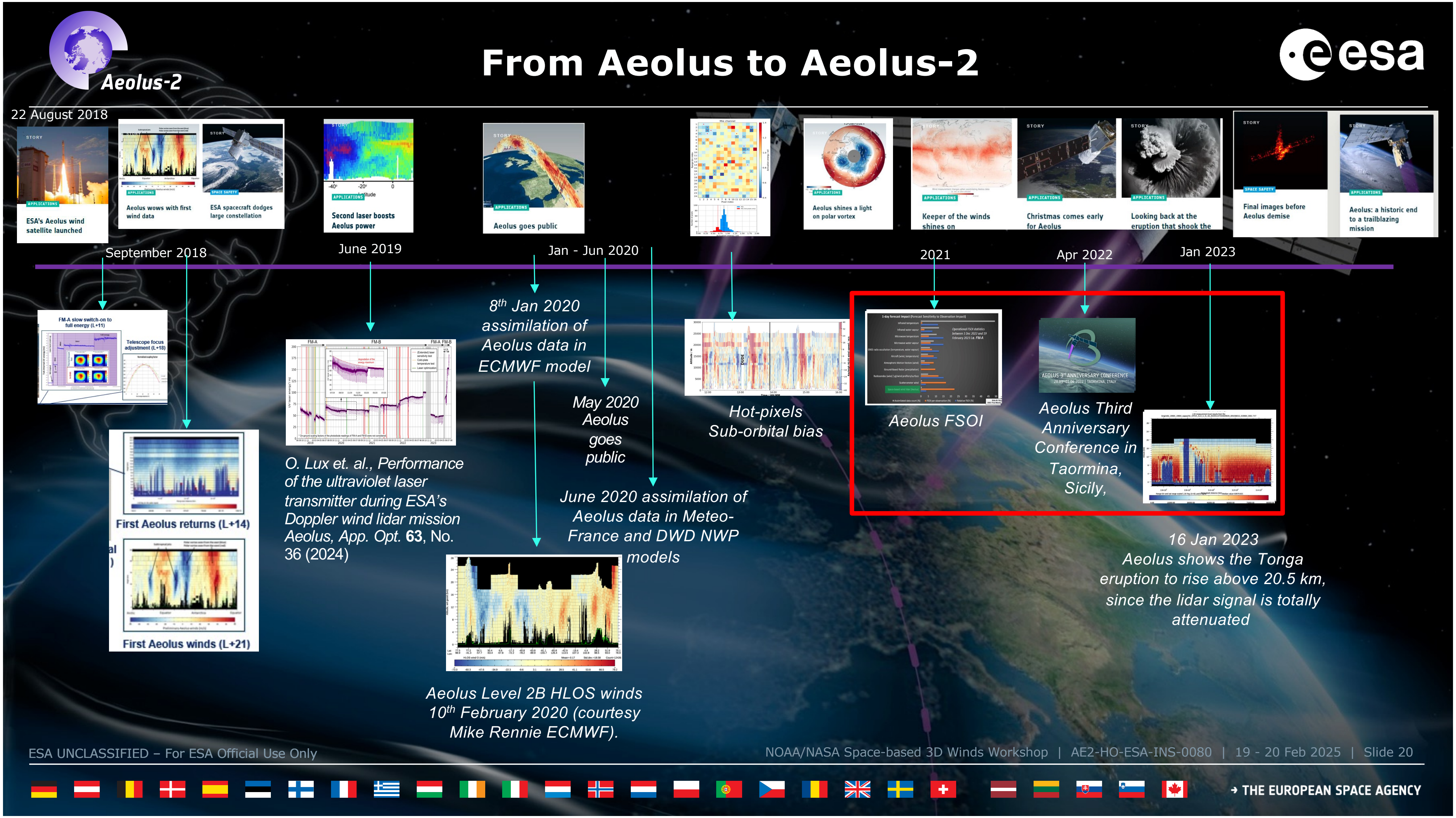
Aeolus measurements showing complete attenuation in the region of the Hunga Tonga volcanic explosion on January 15th, 2022.



Aeolus measurements showing the progression of the Hunga Tonga plume on 18th January as it passes westwards and widens across Australia.



Aeolus measurements on January 24th after changing the vertical range bin settings to 30km altitude to capture the rising ash plume of the Hunga Tonga explosion


Aeolus-2
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Aeolus Level 2B HLOS winds 10th February 2020 (courtesy Mike Rennie ECMWF).
Hot-pixels
Sub-orbital bias
Aeolus FSOI
Aeolus Third Anniversary Conference in Taormina, Sicily,
16 Jan 2023
Aeolus shows the Tonga eruption to rise above 20.5 km, since the lidar signal is totally attenuated
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From Aeolus to Aeolus-2

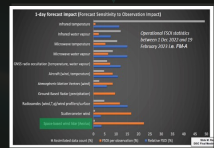
Aeolus Mission Manager, Tommaso Parrinello, Heralding the start of the Aeolus Third Anniversary Conference in Taormina said,
"I believe that the best is still to come, and I'm pleased to announce that with a switch of the laser we are extending the lifetime of this remarkable mission hopefully for another year."

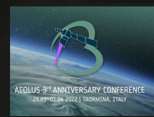
Mike Rennie of the European Centre for Medium Range Weather Forecasts (ECMWF) at Taormina conference: ***"Forecast Sensitivity Observation Impact shows that Aeolus is amongst the most important satellite missions, which is an impressive result for a demonstrator."***

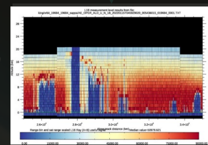
Gemma Halloran of the UK Met Office, where an expanded Aeolus dataset will be operational in May, concurred, saying, ***"Almost all weather models improved with the assimilation of Aeolus data."***

Vivien Pourret of Météo France also presented data that put Aeolus amongst the best instruments for improving weather forecasts, third overall in terms of improvement per observation. He noted, ***"The goal is to operationally assimilate Aeolus data for as long as possible."***

ESA's Director of Earth Observation Programmes Simonetta Cheli in her opening address in Taormina:
"The value of Aeolus is not only scientific, but also economic and societal," *… and ..*
"Following the success of Aeolus and the operational assimilation of data into weather forecast models, it's clear there is growing support for a follow-on mission."

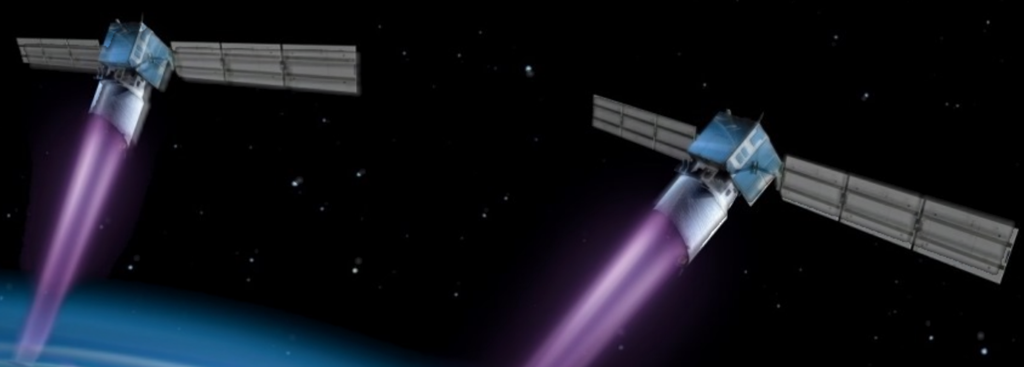






Aeolus-2 / EPS-Aeolus

Aeolus-2



Aeolus-2/EPS-Aeolus Programme Overview & Status

Workshop on Space-based 3D Winds, College Park - US, February 19-20, 2025

Ben Boyes (Aeolus-2 Project Manager) & Rémy Chalex (EPS-Aeolus Project Manager)

Aeolus-2 / EPS-Aeolus Mission & Objectives

Primary Mission Objective:

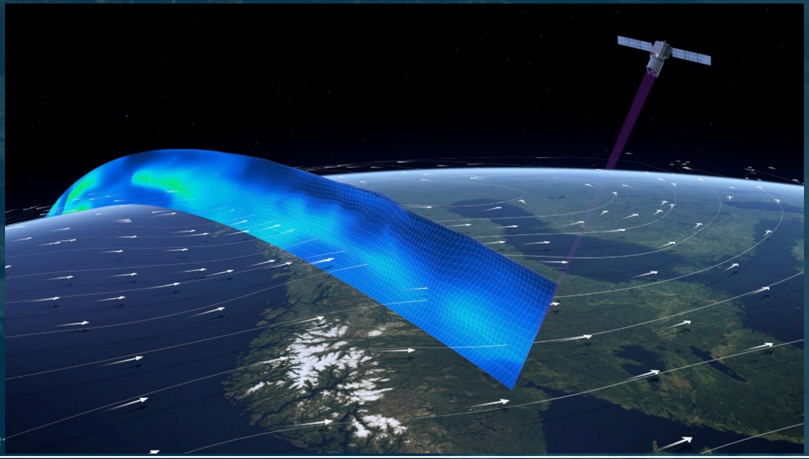
- Measure wind profiles throughout the troposphere and the lower stratosphere with a vertical resolution and accuracy meeting Numerical Weather Prediction (NWP) requirements

Secondary Mission Objectives:

- Measure aerosol profiles by measuring the atmospheric optical properties
- Piggyback of a Radio Occultation instrument identical to EPS-SG's (/MetOp Second Generation).

Mission Parameters:

- Mission shall be operational (i.e. high availability & reliability)
- Mission shall maximise reuse of existing assets (e.g. Ground Stations, processing IF …)
- Mission duration: 10+ years
- Spacecraft lifetime: 5.5+ years (vs. 3 years for Aeolus)



Social Economic Benefit Study

Social Economic Benefit Study (SEB)

- Conducted by an external consultant (former MetOffice) & a former EUMETSAT Director General
- Same methodology used for EPS-SG SEB (validated by World Bank)
- EPS-Aeolus estimated to reduce forecast error by 2-3.5%

EPS-Aeolus estimated benefit to cost ration → 1:20 [1,2]

- Report & Executive summary available from EUMETSAT's website

https://www-cdn.eumetsat.int/files/2023-11/Summary_FINAL.pdf

[1] The 1:20 ratio is considered a conservative estimate

[2] The SEB was completed before the final industrial costs were available, and is currently being updated with the new data available but is anticipated to remain higher than 1:15.

Aeolus-2 / EPS-Aeolus Programme Overview

Aeolus-2 EUMETSAT esa

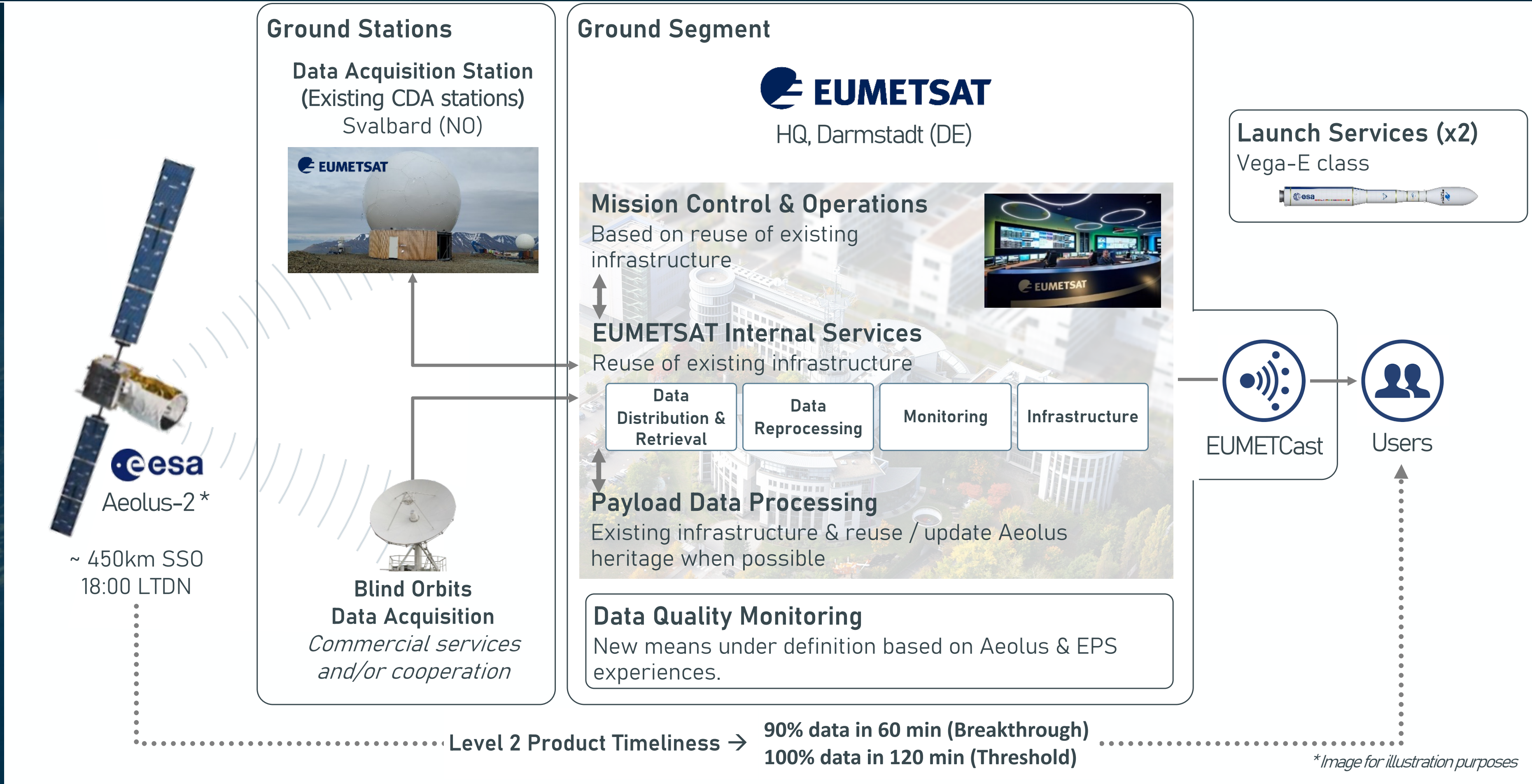
Programme Structure:

- Aeolus-2 / EPS-Aeolus is a collaboration between ESA and EUMETSAT to develop two satellites to implement the technology developed on Aeolus, for 10+ years of operational capability.
- ESA will develop the protoflight model (PFM) with a contribution to the development costs provided by EUMETSAT.
- ESA will procure the recurrent model (FM2) which is fully funded by EUMETSAT.
- EUMETSAT provide the launchers, ground segment and operate the satellites.
- The ESA contributions are gathered together as the Aeolus-2 project, and the EUMETSAT contributions as the EPS-Aeolus Programme, but conceptually they represent a single endeavour.
- The Satellite carries two payloads, the Doppler Wind Lidar (DWL) Instrument and Radio Occulation (RO) Instrument.

Current Status:

- Pre-developments have been running for key technologies, and the DWL Instrument and Platform architecture definition for three years already.
- The implementation programme starts in earnest this year next month.
- The PFM Satellite is planned for launch in 2034 and the FM2 Satellite in 2039.

Aeolus-2 / EPS-Aeolus System Overview

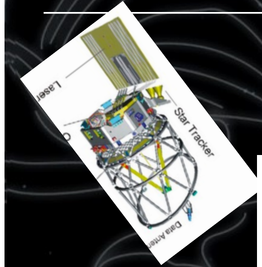


Aeolus-2 New Requirements

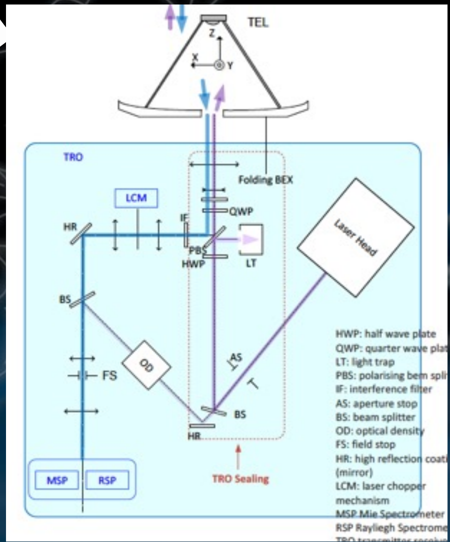
- Longer lifetime from 3.3 years to 5.5 years with 2 satellite covering 10 years operation
- 67 Vertical Samples (66 +1 for SBKG)
- Vertical sampling resolution down to 125m
- Horizontal sampling resolution down to 3km
- Higher overall robustness for an operational mission
- New Cross-polarization channel for aerosol

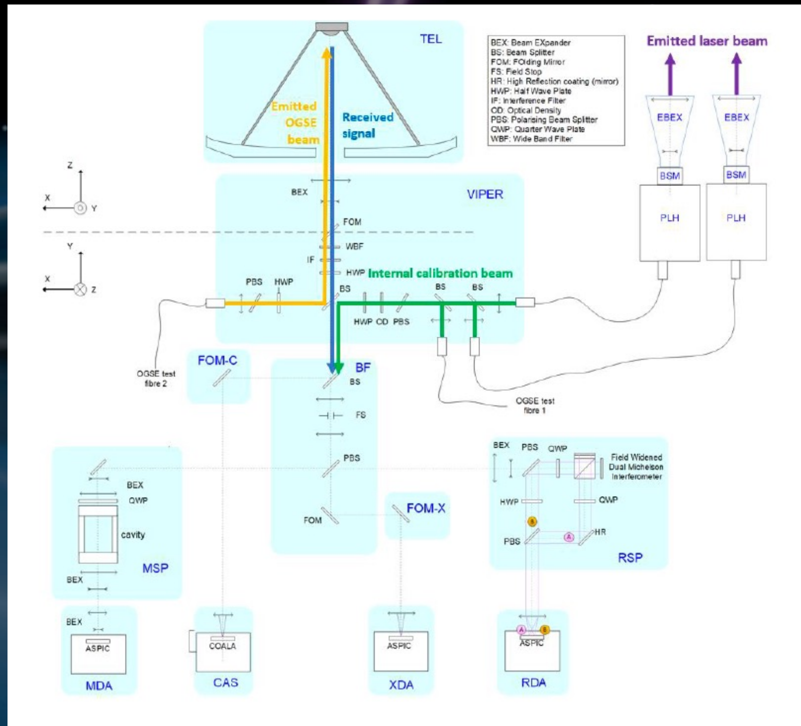
	Aeolus-2	Aeolus
Horizontal resolution	100km	100km
Vertical range	0-40km	0-20km
Vertical resolution (PBL/TP/SL)	0.25/0.5/1.0km (breakthrough)	0.5/1.0/2.0km
Number of vertical samples	66+1	24+1
Lifetime	5.5 years	3 years
Additional optional channel	Cross polar	None
Mission	Operational, 2 sat, 10 years	Demonstrator 1 sat, 3 years
Random error	Mie channel < 2 m/s (0-2 km) Rayleigh ch. < 2.5 m/s (2-16 km) Rayleigh ch. < 5 m/s (16-40 km)	Mie channel < 1 m/s (0-2 km) Rayleigh ch. < 2.5 m/s (2-16 km) Rayleigh ch. < 3 m/s (16-20 km)
Unknown bias	1.7 m/s (1σ) @L1b 2.1 m/s (3σ) @L2	0.7 m/s (1σ) 2.1m/s (3σ)

Aeolus-2 Bi-Static Architecture



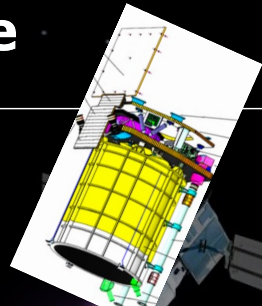
Aeolus vs Aeolus-2





Mono-Static

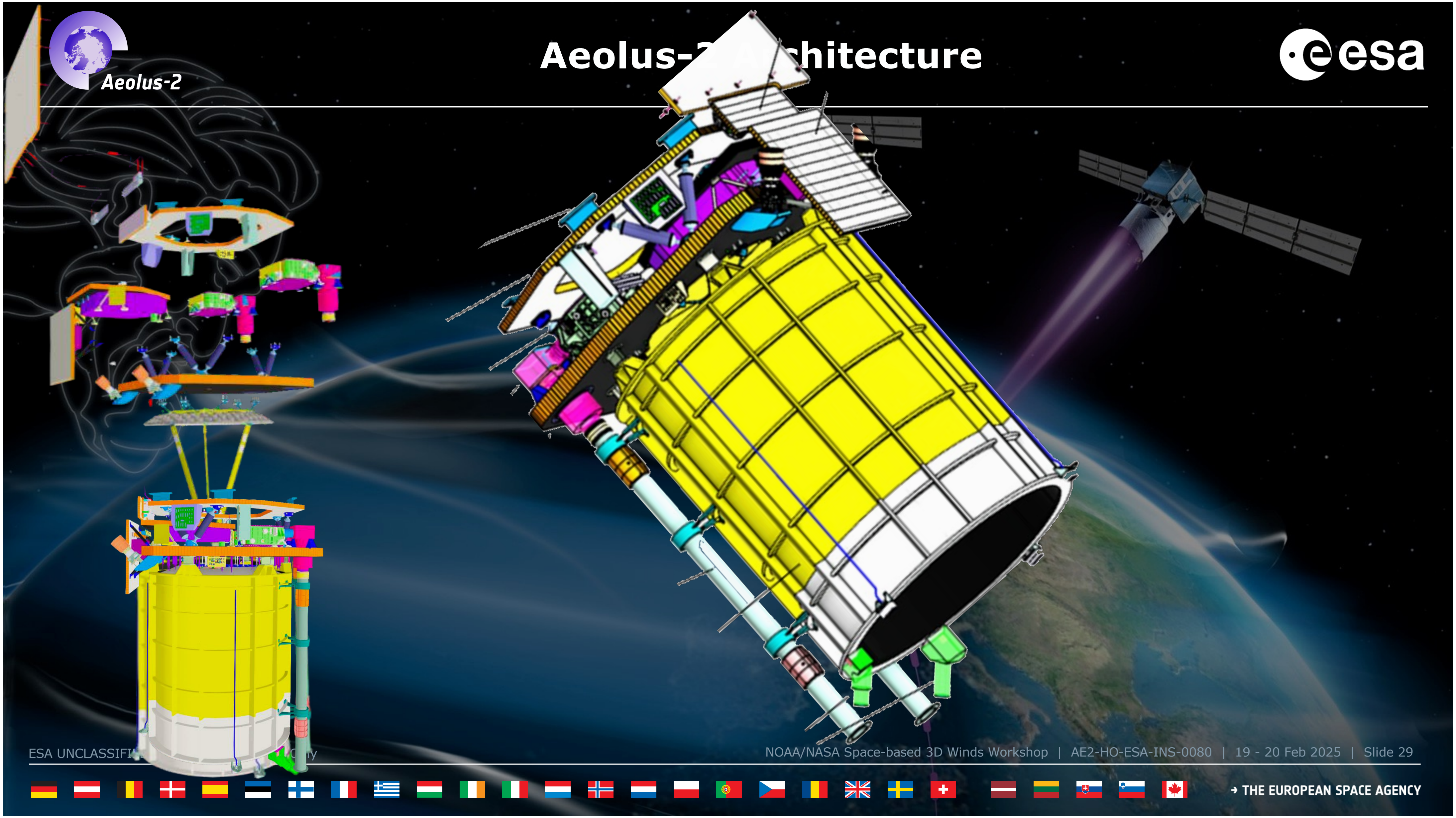
Bi-Static

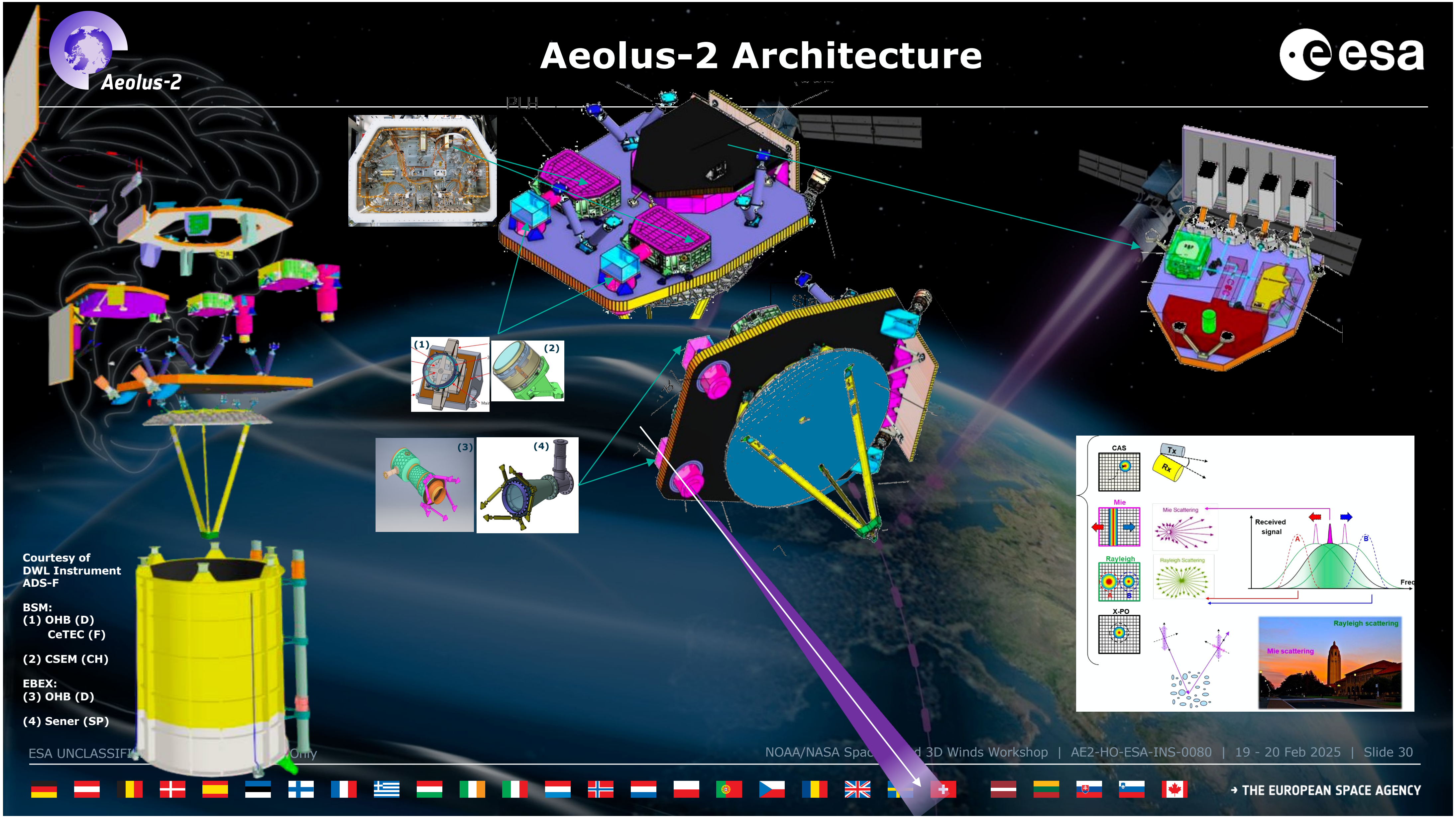


Mono-static to BI-static architecture
Tx path separated from Rx

- Removes Single Point Failures (LID in common Tx/Rx optics in the emit path, the Laser Chopper Mechanism, Flip-Flop Mechanism)
- Provides much greater robustness to LIC/LIC as has 2 fully redundant and separate emit paths
- Induced design requirements: Line of Sight stability control
- Development of Co-Alignment loop Tx-to-Rx
- Imposes for laser transmitter divergence and primary mirror deformations.

Aeolus-2 Architecture




Aeolus-2
Aeolus-2 Architecture
esa
PLH
(1)
(2)
(3)
(4)
Courtesy of
DWL Instrument
ADS-F
BSM:
(1) OHB (D)
CeTEC (F)
(2) CSEM (CH)
EBEX:
(3) OHB (D)
(4) Sener (SP)
CAS
Tx
Rx
Mie
Mie Scattering
Received signal
A
B
Freq
Rayleigh
Rayleigh Scattering
X-PO
Rayleigh scattering
Mie scattering
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From Aeolus to Aeolus-2

Aeolus Take Away

The mission has exceeded its designed lifetime (3-years).

First successful demonstration of operation of a ultraviolet laser in space with stable performance of both lasers

Aeolus has been providing globally measurements of HLOS wind profiles for almost five years surpassing any DWL flown before.

- unprecedented insights into global wind patterns and aerosol distribution
- enhancing our ability to forecast weather
- monitor climate change and improve air quality monitor

It has achieved its main objectives with its data assimilated operationally by the most important meteo forecasting centres in Europe

Aeolus has been an innovative and unique mission. It is can be truly considered as THE PATHFINDER for future DWL and has played a fundamental role in convincing ESA and EUMETSAT to develop EPS/Aeolus-2

Aeolus-2 Way Forward

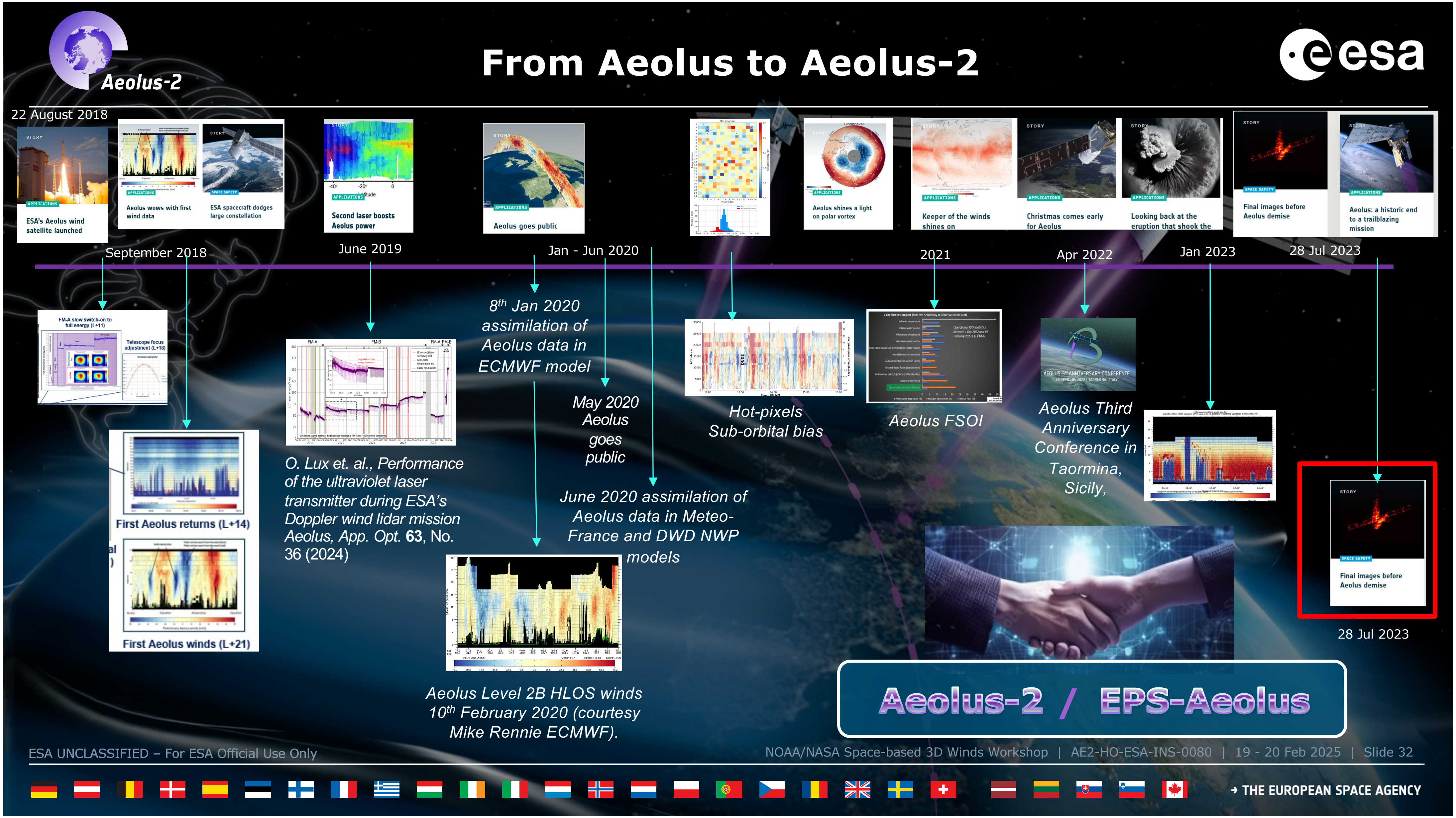
Operational mission to cover 10 years of wind observation with a series of 2 satellites with nominal life of 5.5 years

More robust and easy to operate

Better SNR:
Higher energy laser
Link budget (M1 improved design)

Increased number of vertical samples 67 vertical bins
Increased vertical sampling resolution (125 m) and
Horizontal sampling resolution (3 km)

Aeolus-2 will benefit from Aeolus legacy and EarthCARE/ATLID heritage with an improved and more stable laser and proved bi-static architecture (co-alignment)



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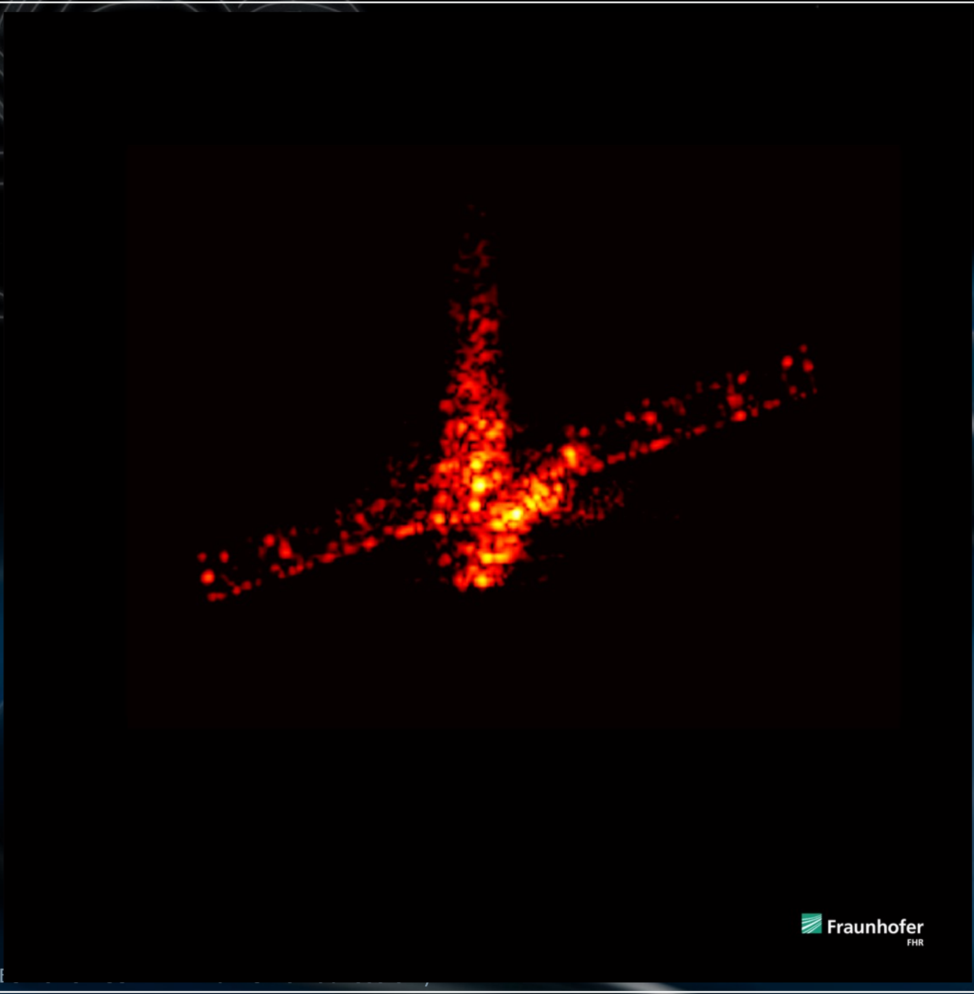
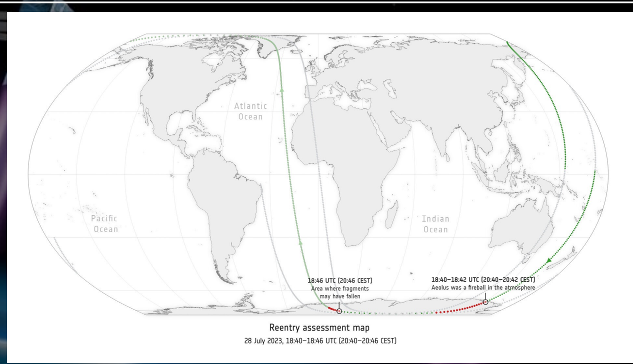
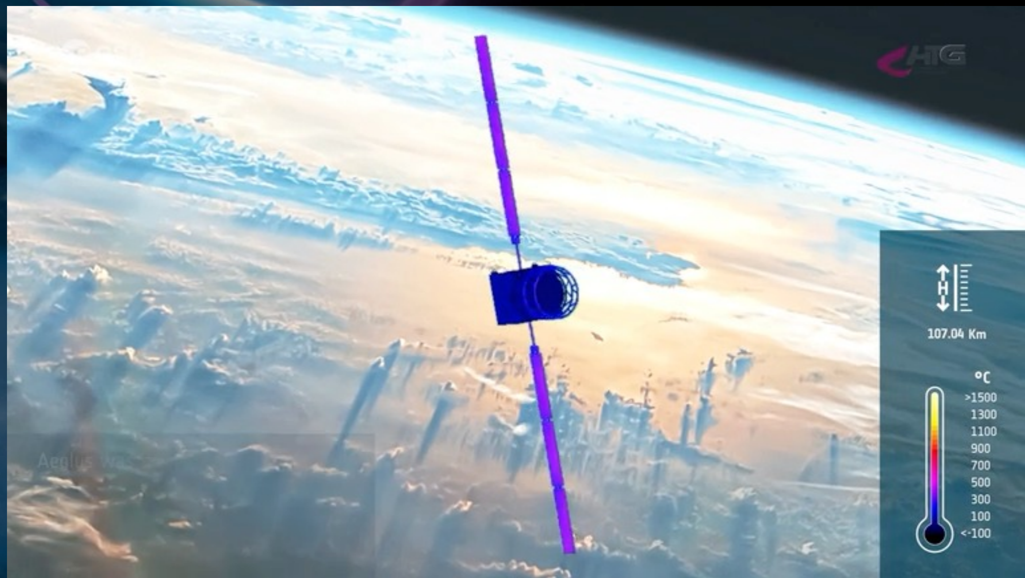
Aeolus Assisted Re-Entry







Aeolus Assisted Re-Entry

Thank you Aeolus

and

Thank for your attention

B. Boyes – Aeolus-2 Project Manager
M. Porciani – Aeolus-2 Payload Manager