ESA's Wind Mission Aeolus - the first Doppler Wind Lidar in space

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European Space Agency

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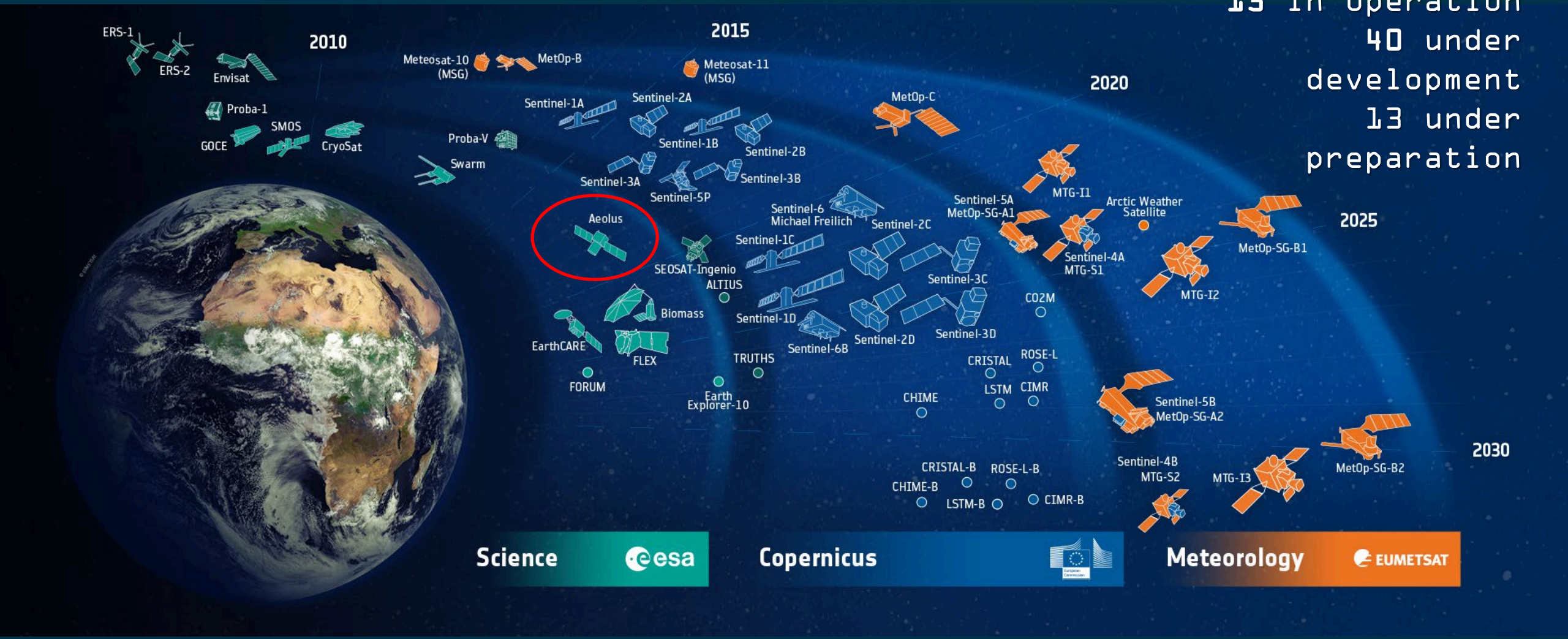
3 December 2020, 16th Appleton Space Conference virtual event

ESA's Earth Observation Satellite Programme

15 in operation
40 under development
13 under preparation



Mission objectives

Scientific objectives

- To improve the quality of weather forecasts (impact)
- To advance our understanding of atmospheric dynamics and climate processes

Explorer objectives

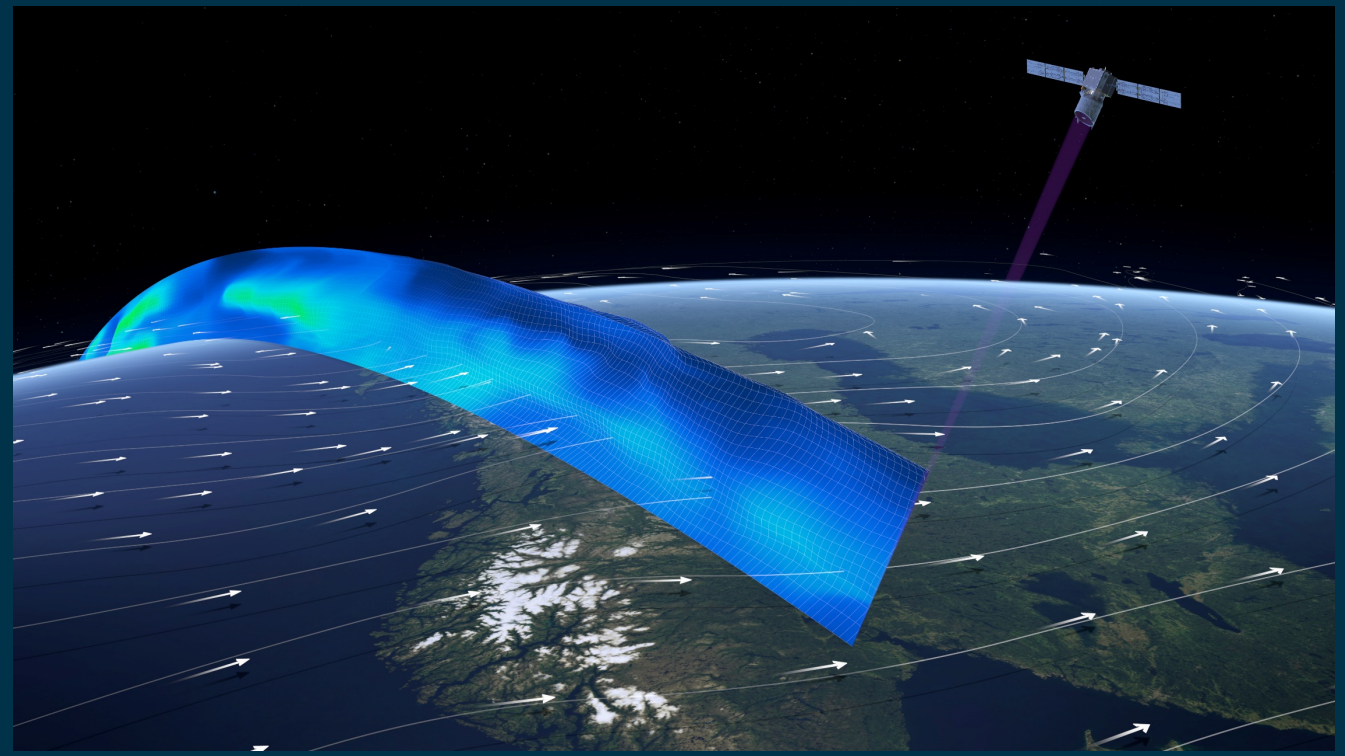
- Demonstrate space-based Doppler Wind LIDARs potential for operational use

Observation means

- Provide global measurements of horizontal wind profiles in the troposphere and lower stratosphere
- Spin-off products are atmospheric extinction and backscatter coefficient profiles

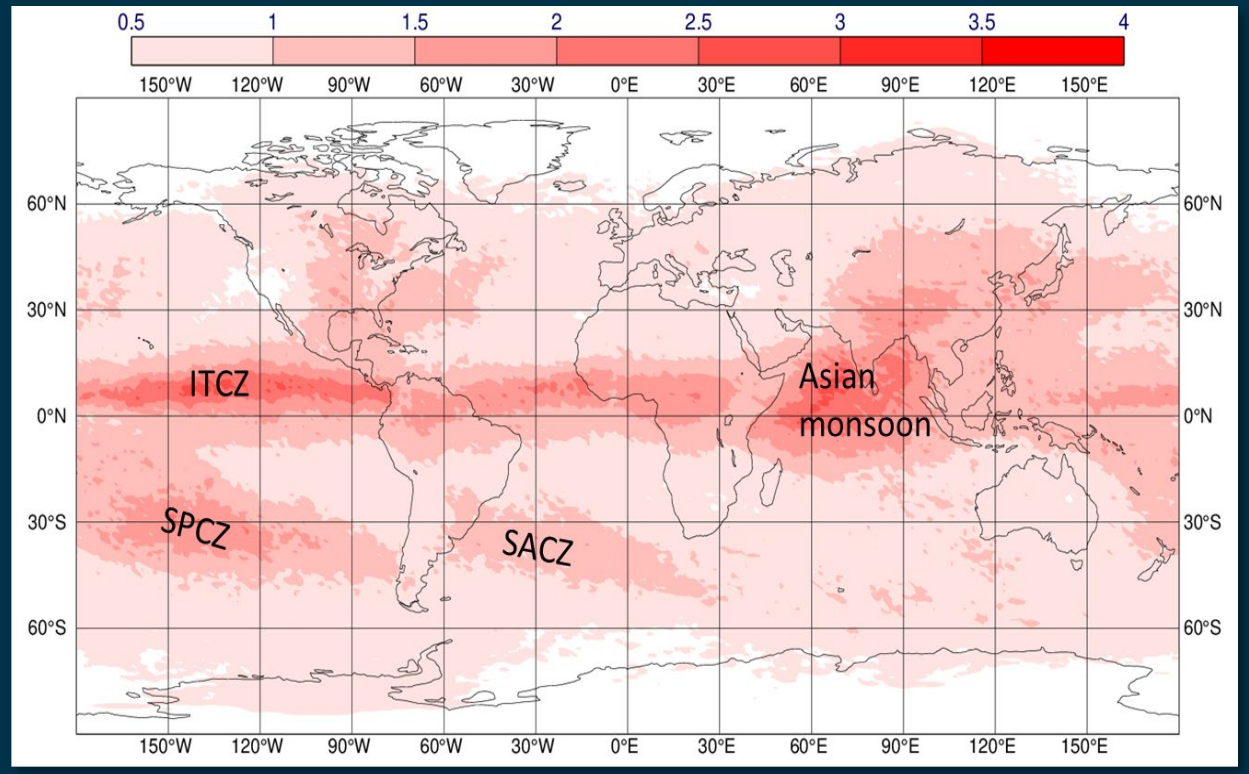
Payload

- ALADIN: Atmospheric LAser Doppler INstrument



Examples of scientific benefits seen from Aeolus

- Weather centers in Europe, the US, Canada and India see significant positive forecast impact of Aeolus winds when assimilated in their models
- Aeolus shown to provide important wind information in data sparse areas (Tropics, Southern Hemisphere, Polar areas, and in the upper troposphere and lower stratosphere) → largest forecast impact here
- Forecast centers assimilate Aeolus winds in their daily weather forecasts
  - Since 2020: ECMWF, DWD, Météo-France
  - Will start soon: UK MetOffice, Indian NCMRWF
- Aeolus captures vertically propagating waves driving large-scale dynamics
- Recent changes to stratospheric circulation observed by Aeolus (2019/2020 QBO disruption)

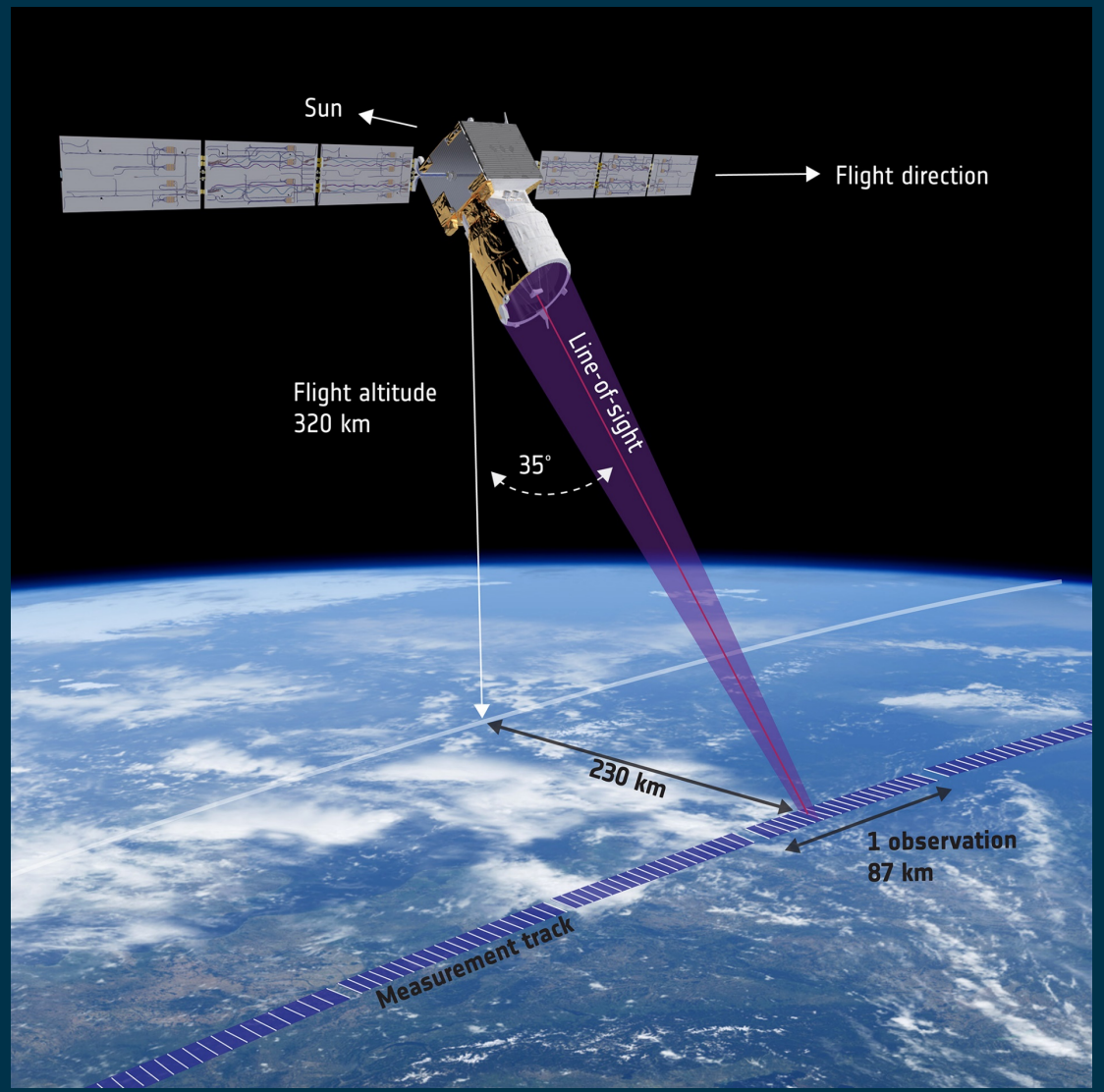


Standard deviation of change in zonal wind analysis (m/s) at ~10 km in the ECMWF model when assimilating Aeolus winds from 4 April to 19 August 2020, courtesy M. Rennie ECMWF

Aeolus mission and measurements concept

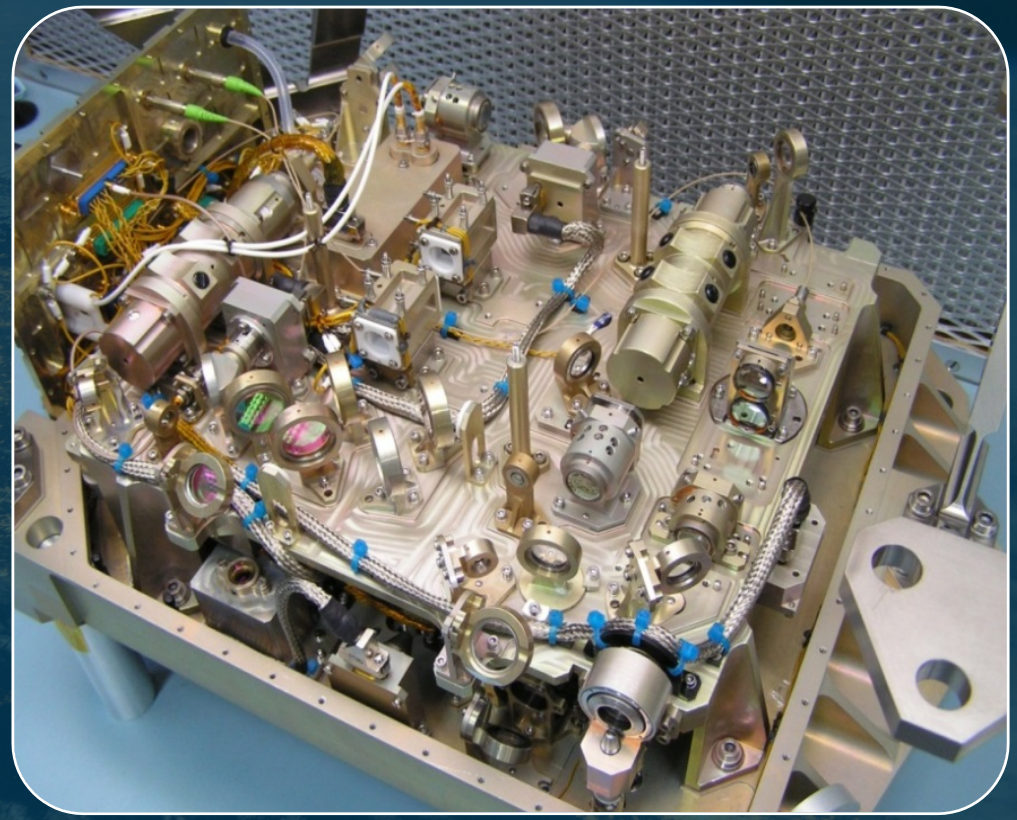
- Launched on 22 August 2018, 3 years lifetime
- Satellite at 320 km sun-synchronous orbit, dawn/dusk
- Satellite prime: Airbus UK
- Instrument Prime: Airbus France

- Aladin instrument:
  - Direct detection UV Doppler Wind Lidar (355 nm), 60mJ laser output, 50 Hz PRF, 2 receiver channels
  - Mie receiver to determine winds from aerosol & cloud backscatter (Fizeau)
  - Rayleigh receiver to determine winds from molecular backscatter (Double edge Fabry-Perrot)
  - The line-of-sight (LOS) points 35º from nadir to capture profiles of single component horizontal wind
  - Ground return used for attitude correction and instrument calibration



Aladin instrument: challenges during development

- One of the most sophisticated optical instruments ever to be put in orbit (EE)
- High-power ultraviolet (UV) laser transmitter containing ~80 optical functions and 2 wavelength conversion
- High atmospheric backscatter sensitivity via 1.5 m telescope, focused on 80 micron field stop and etalon spectrometers
- **High precision frequency shift measurements:**
  - **Doppler Wind Lidar** principle
    - $\Delta f = 2*f_o*V_{LOS}/C$
    - V_{LOS}=1 m/s
      - Δf = 5.64 MHz
      - $\Delta f / f_o = 6.7\ 10^{-9}$
      - $\Delta\lambda = 2.4\ 10^{-15}$ m ($H^+ \approx 1.7\ 10^{-15}$ m)

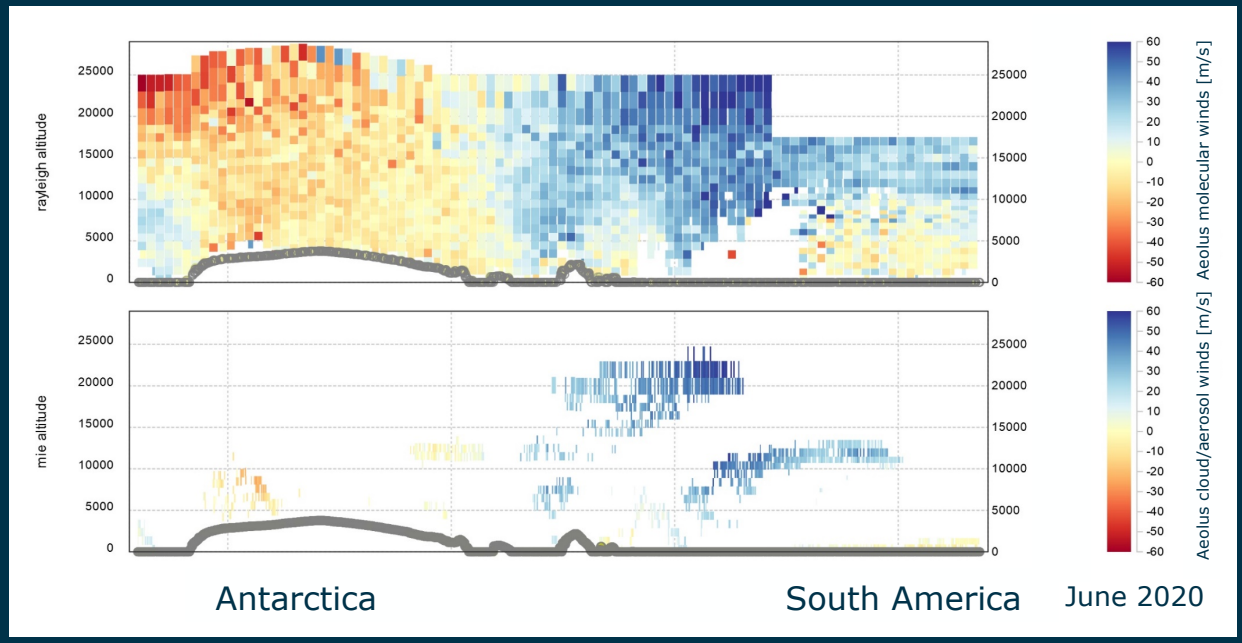


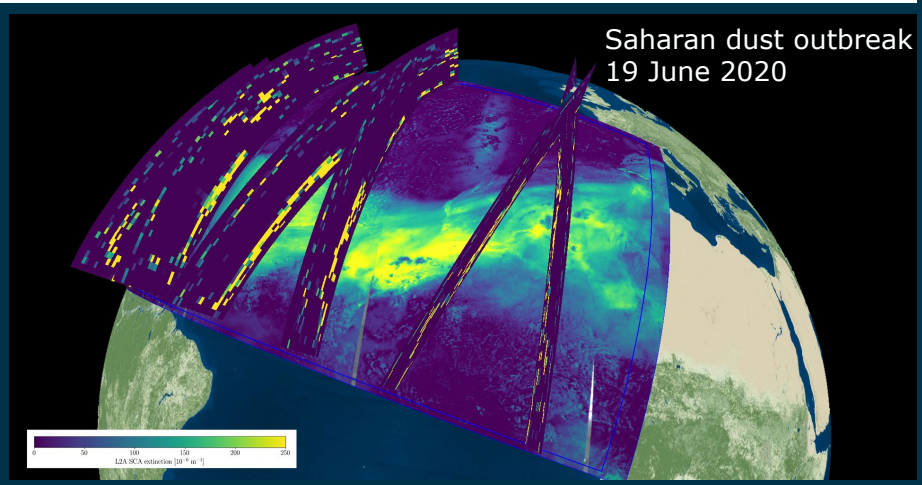
Aeolus data products

- **Primary product**
  - Profiles of 1-D winds (east-west component) from the surface up to 30 km (winds from molecular and particle backscatter)
  - Available in near-real-time, 3 - 7 m/s accuracy, low product biases (< 1 m/s)

- **Spin-off product**
  - Profiles of atmospheric backscatter and extinction coefficient products
  - Allows to determine aerosol and cloud layer heights
  - Experimentally used in CAMS to improve aerosol layer height and transport

- **Products under investigation / development**
  - Ocean surface winds, ocean color at 355 nm

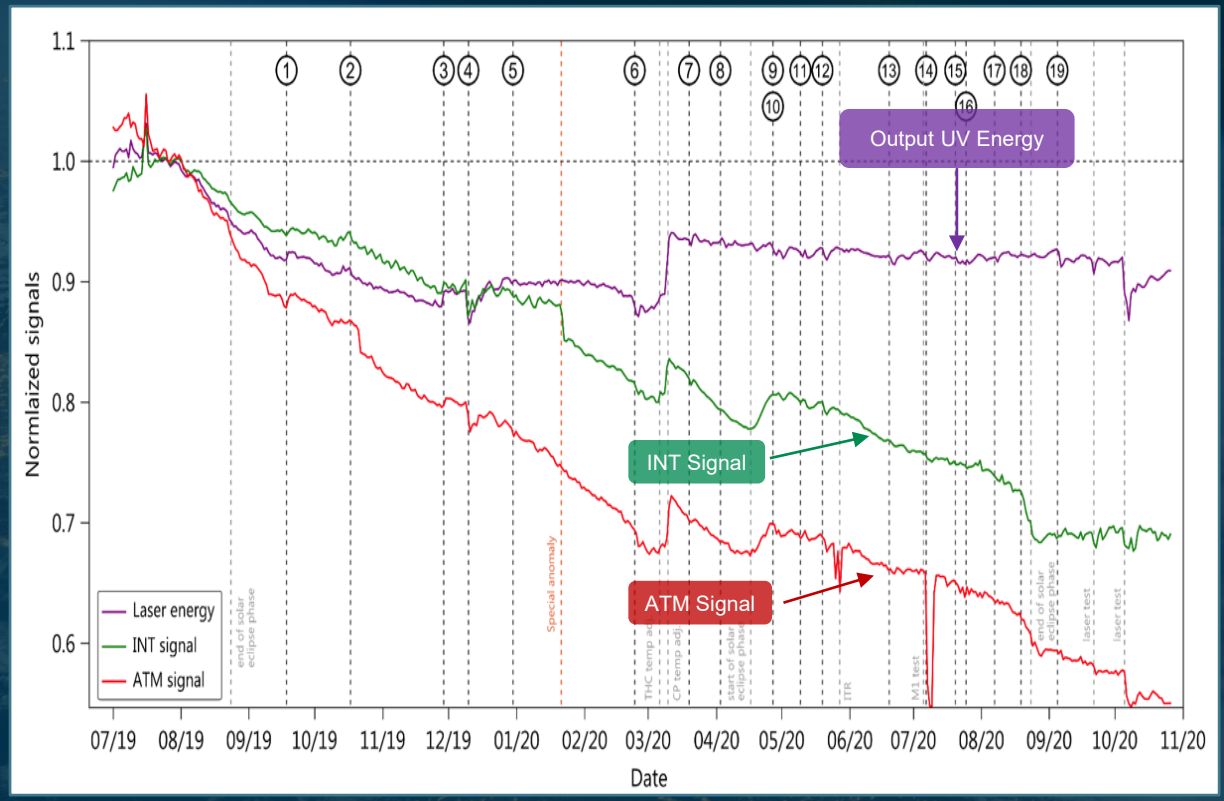




https://www.esa.int/Applications/Observing_the_Earth/Satellites_track_unusual_Saharan_dust_plume

Aeolus mission performance in-flight

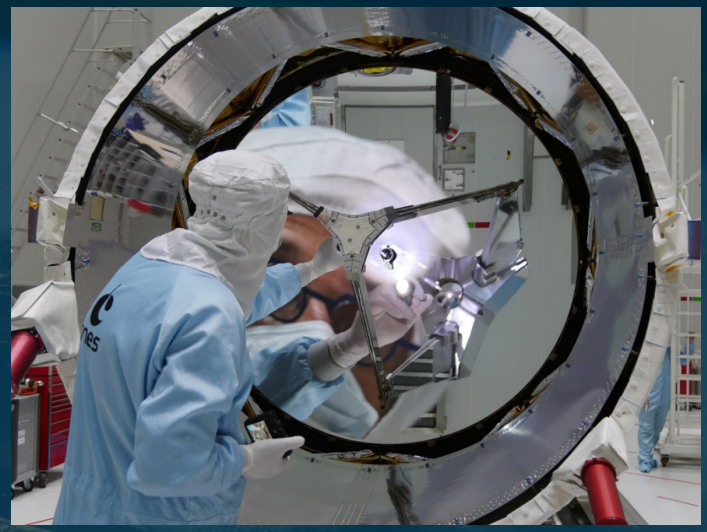
- Satellite performs well: degradation, including consumables and life limiting elements, within specifications. Number of special operations tasks high
- The redundant flight laser (FM-B) performs well in terms of UV output energy, currently 68 mJ following recent optimizations
- Remaining challenge: continuous decrease of atmospheric return signal → slowly increasing wind random errors with time
- Investigations at ESA, industry and external expert teams on-going, roadmap to mitigate signal loss established and kept up-to-date
- Full atmospheric signal recovery probably not achievable, but mitigations actions expected to yield performance increase (e.g. M1 thermal optimisation).
    - More radical options include possible orbit lowering and/or switch-back to main laser transmitter

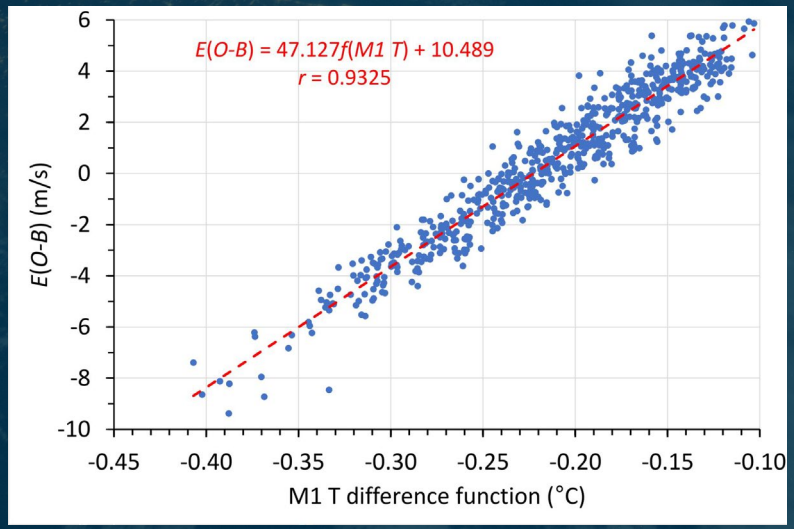


Courtesy O. Lux (DLR and Aeolus DISC)

Wind biases caused by telescope temperature variability

- The Aladin M1 telescope (1.5 m Ø) known to be temperature sensitive (Top of Atmosphere (TOA) radiance variability), hence active thermal control implemented in mission design
- Ground returns (zero Doppler shift) intended to correct potential residual wind speed errors in L2 wind product
  - Hampered by surface albedo variability and lower than expected in-flight performance → fewer valid ground returns
- Aeolus DISC team found root-cause for Aeolus wind bias variability along orbits using [Observation (O) - Forecast model background (B)] statistics
  - Telescope thermistor readings following TOA radiance, differences temperatures center versus edge impact alignment
  - Telescope thermal control hence less effective than expected
- Aeolus DISC and ESA developed effective on-ground processing correction scheme (implemented since 20 April 2020)
- Further optimization of M1 telescope thermal control under investigation by industry

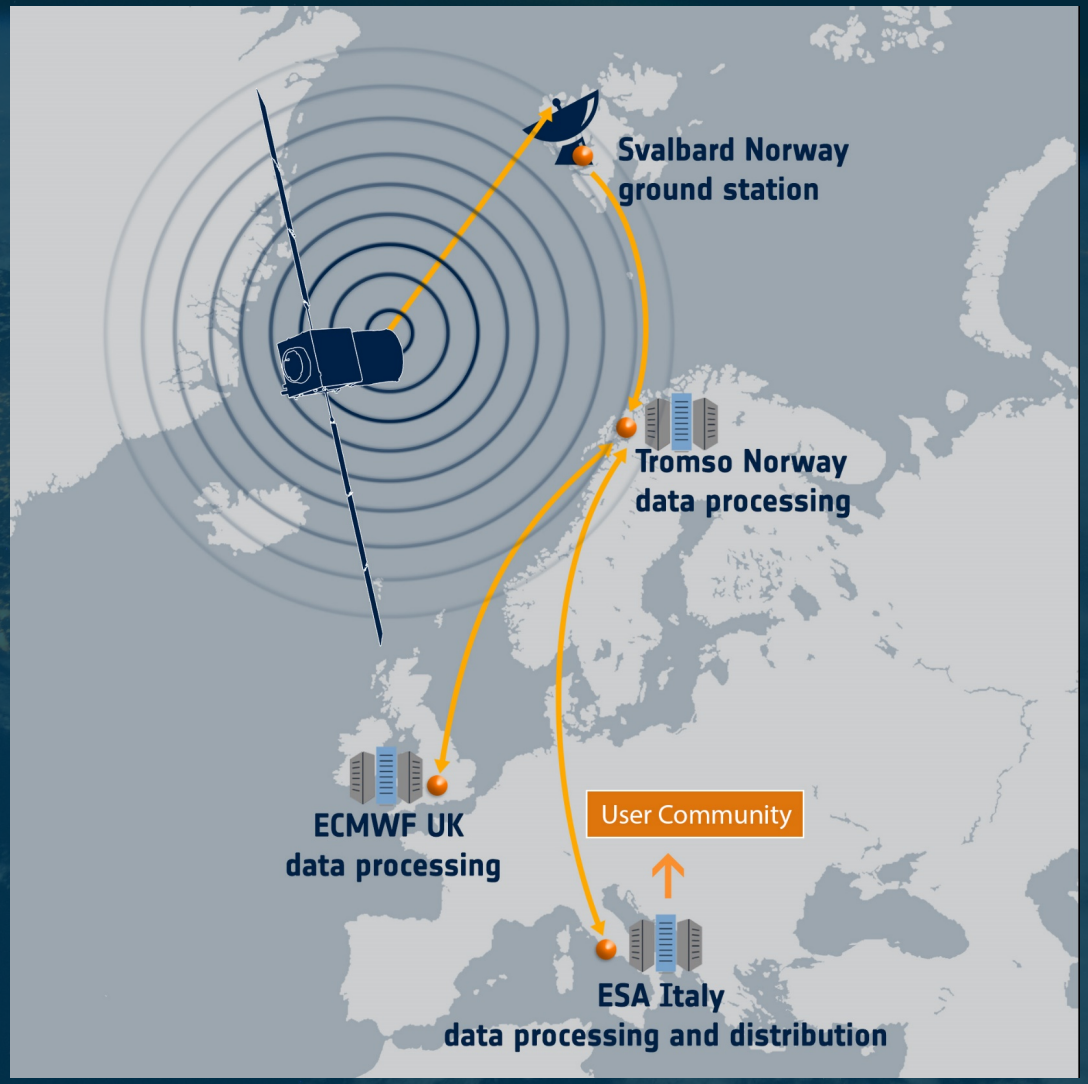




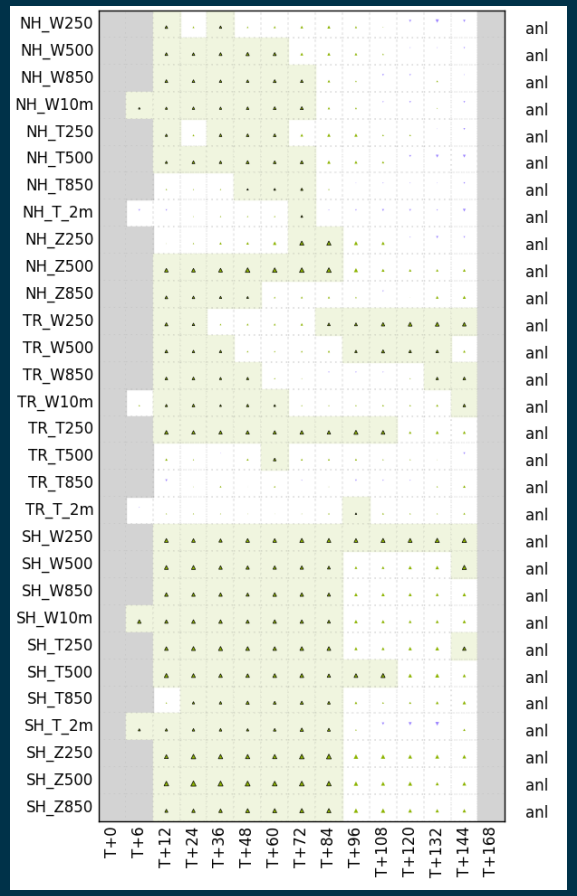
Courtesy M. Rennie (ECMWF and Aeolus DISC)

Aeolus Ground Segment

- On-ground data processing facility worked excellent from the start, allowing L2B wind product output in near-real-time (NRT) since ~2 weeks after launch.
- Data acquisition performance excellent, performance above 98% and on average 99.5% since October 2018
- Since 20 December 2018, CAL/VAL teams (including NWP centers across the world) have had access to the Aeolus scientific data in near-real-time (NRT)
- Since February 2019, more than 98% of the data have been available in NRT
- On 12 May 2020 the Aeolus L1B and L2B NRT data were publically released
- First reprocessed dataset (Q2+Q3 2019 data) released in October 2020, whole dataset will be reprocessed in 2021

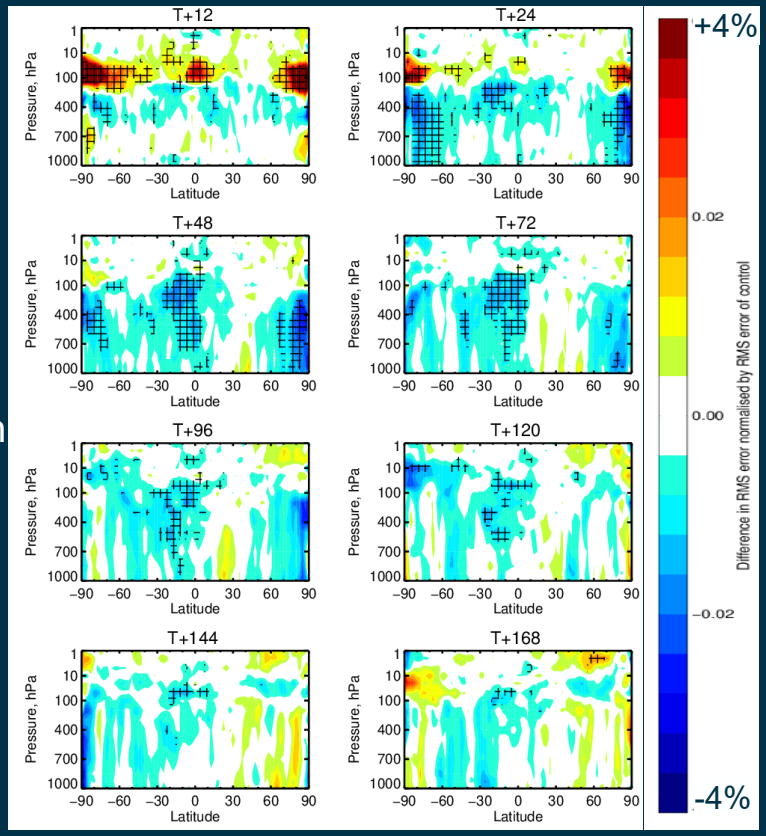


Scientific results: reporting @ Aeolus 2020 workshop (1/3)



Courtesy ©G. Halloran (UK MetOffice)
Example of UKMO model score card. Green (large triangles) indicate positive (significant) impact of Aeolus Mie winds on forecast of wind, temperature, and geopotential at different heights and geographical regions

- Statistically significant positive impact seen by ECMWF and MetOffice in their weather forecasts
- ECMWF started operational assimilation 9 January 2020 ~16 km
- UK MetOffice plans to start assimilating Aeolus winds in December 2020

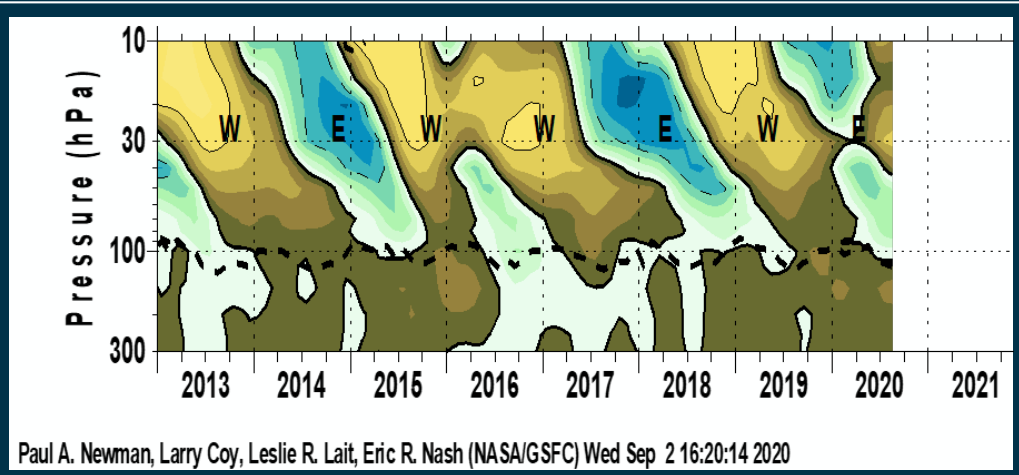


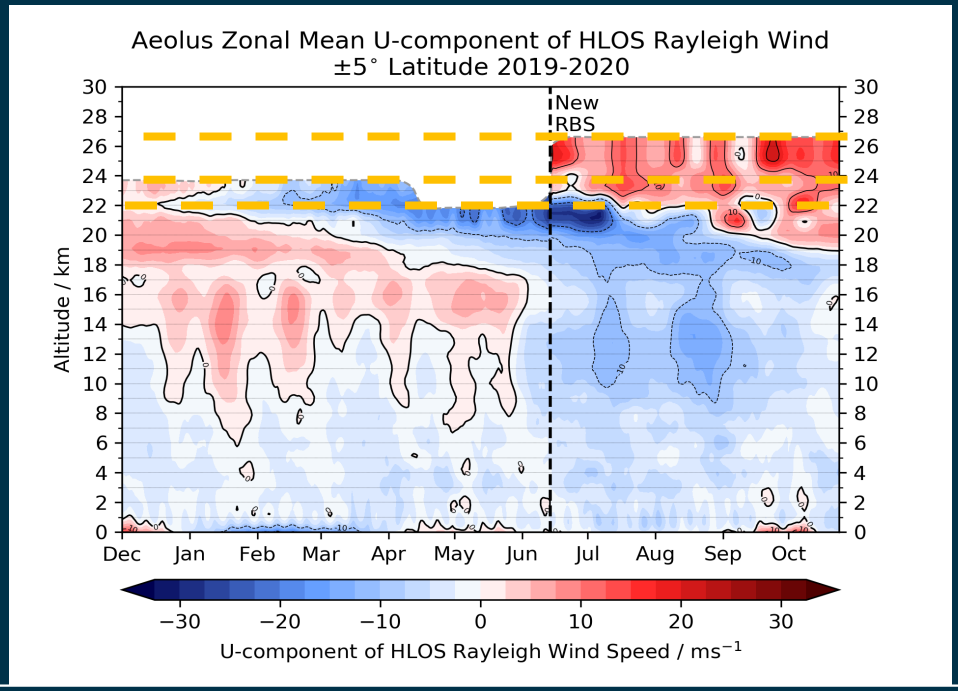
Courtesy ©M. Rennie (ECMWF and Aeolus DISC)
Example of ECMWF model forecast improvements at different forecast lengths (T hours) when assimilating Aeolus Mie and Rayleigh winds.
Blue colours: positive impact.
Hashed: statistically significant impact.

Scientific results: reporting @ Aeolus 2020 workshop (2/3)

- Climate change cause changes to Earth's large-scale circulation and their natural variability such as the QBO, Monsoon, MJO, El Niño, tropospheric and stratospheric jet streams, etc.

- Stratospheric Quasi-Biannual Oscillation (QBO) circulation disruption appeared for the first time in 2016, and reoccurred in 2019/2020
  - https://www.essoar.org/doi/10.1002/essoar.10503358.2
- QBO disruption observed by Aeolus
- Scientific investigations on-going using Aeolus data addressing the mechanism behind the circulation change





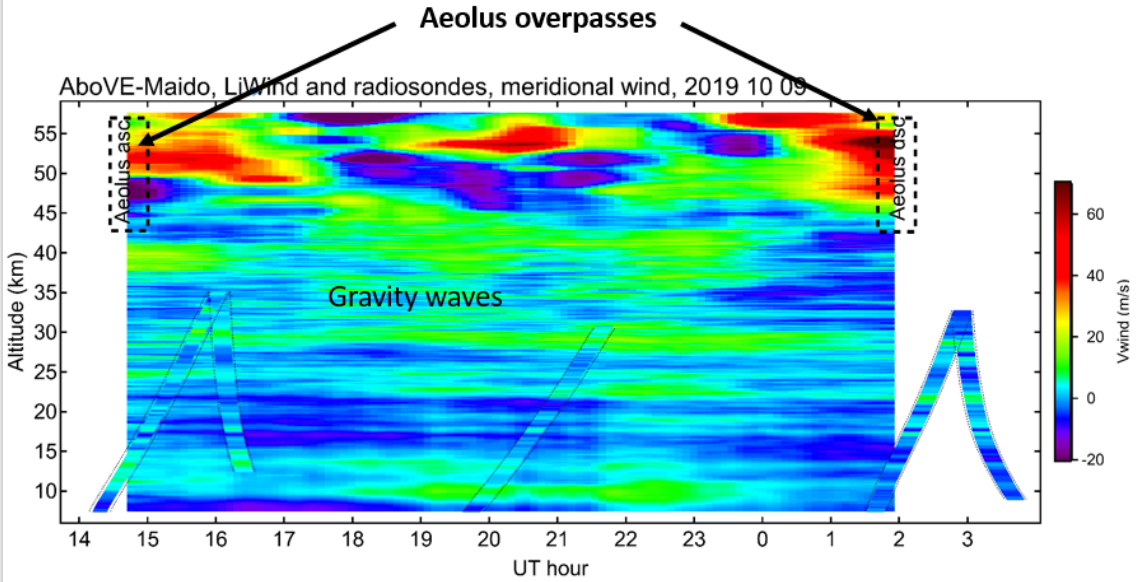
Courtesy ©T. Banyard (University of Bath) and S. Osprey (University of Oxford) et al.

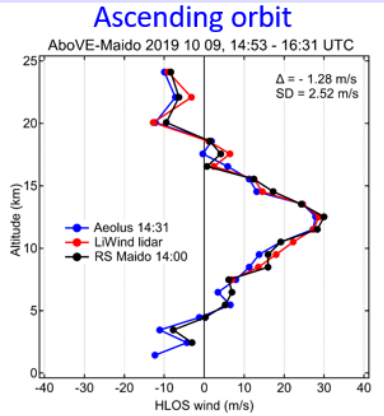
Scientific results: reporting @ Aeolus 2020 workshop (3/3)

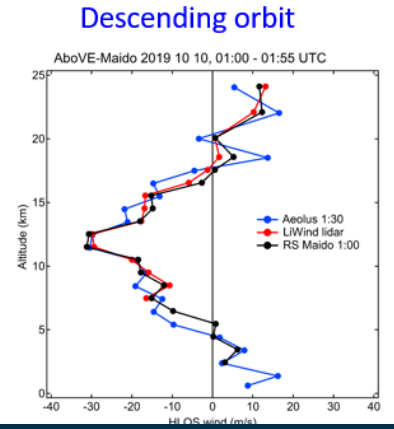
- Aeolus CAL/VAL with French ground-based lidars at Observatoire de Haute-Provence and La Reunion, showing vertical propagation of gravity waves, detected with Aeolus

AboVE-Maido campaign: Aeolus validation using LiWind and radiosondes

Example of Cal/Val measurements with 3 radiosoundings and continuous LiWind operation from dusk till dawn: meridional wind





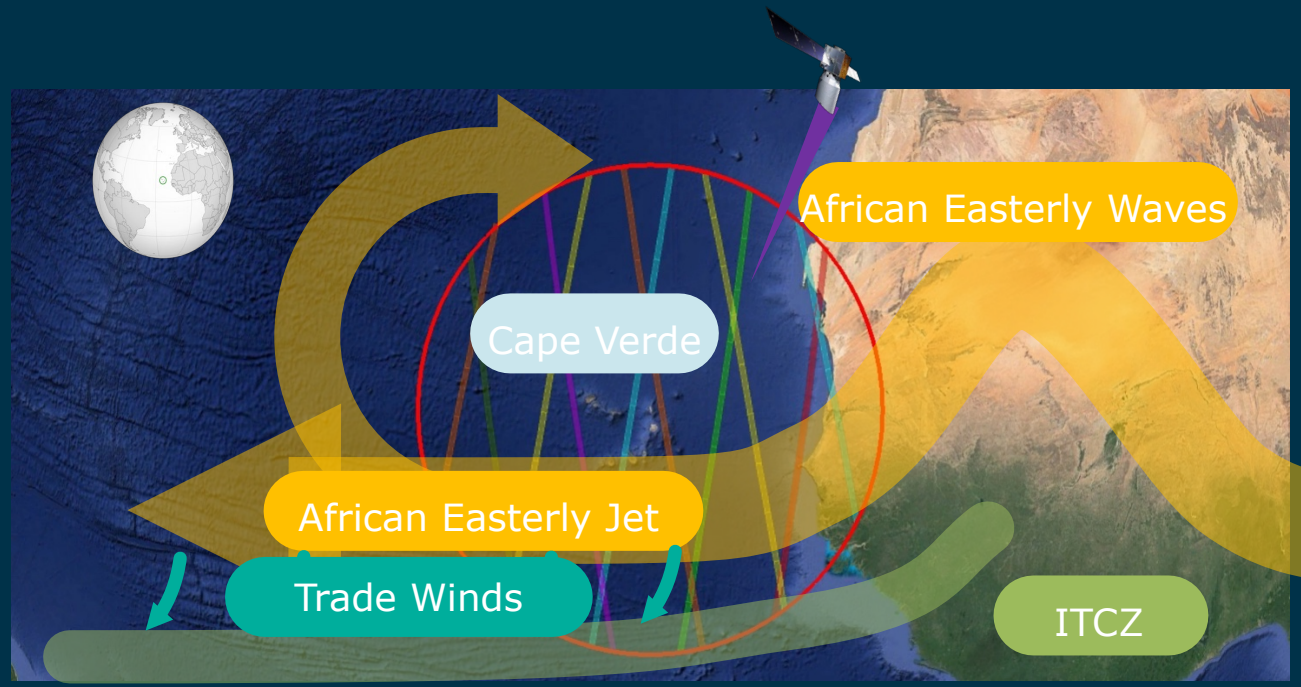


- During AboVE-Maido, 3 asc + 3 dsc Aeolus-collocated measurements have been done
- Perfect timing for the balloon launches and LiWind operation on Cal/Val nights
- Aeolus is capable of reproducing vertical structures induced by IGW

Slide shown by ©S. Khaykin et al., (LATMOS, IPSL) at 2020 Aeolus CAL/VAL and Science Workshop
https://amt.copernicus.org/articles/13/1501/2020/

Aeolus Campaigns

- Proof of concept campaigns started in 1980s
- Aladin Airborne Demonstrator (A2D) used on-ground and in aircraft since 2006 (DLR under ESA contract)
- Multiple campaigns ESA, DLR, IPSL, NASA before launch
- Three campaigns by DLR with A2D and reference lidar system since launch
- CNES Stratospheric Balloon experiment Strateole-2 / TAPAPA also in support of Aeolus CAL/VAL
- International tropical campaign for Aeolus wind and aerosol product CAL/VAL and science in July 2021, Cape Verde. International consortium under ESA contract



Aeolus follow-on (Aeolus-2)

- NWP centers have reported statistically significant impact of Aeolus data on their weather forecasts
  - User sent a letter of support for a follow-on mission to ESA and EUMETSAT in 2019
- At Space19+, ESA member states supported a program to further mature the Aeolus technology in preparation of a potential operational follow-on mission in the next generation EOP-SG polar system
  - Phase A/B1 activities on-going at ESA
- Interest to start programmatic steps for operational follow-on expressed by EUMETSAT Council
  - Phase 0/A activities starting at EUMETSAT
- ESA has established a Science Advisory Group with EUMETSAT participation to support user requirements

— New Antarctic ground station for Aeolus increases data flow

With Aeolus built as a research and demonstrator mission, it has shown its worth as an operational mission with the data being used for everyday weather forecasting, paving the way for a possible future fleet of operational Doppler wind lidar satellites in space.

Alain Ratier, Director-General of EUMETSAT, concluded, "EUMETSAT will now push Aeolus data in near-real time to the 4000 users of EUMETCast and to the full WMO community, to give the opportunity to every forecast centre to familiarise with the novel data and measure their value. This user feedback, together with the results of on-going ESA instrument and satellite studies, will support our planning of a possible operational Doppler Lidar mission adding a missing wind profiling capability to our next generation EPS-SG polar system."

http://www.esa.int/Applications/Observing_the_Earth/Aeolus/Aeolus_goes_public

Summary and conclusions

- Satellite now flying since 27 months
- Overall mission performance is good allowing intended scientific exploitation
  - Slow signal loss remain challenging, mitigation measures being implemented
  - Mission recently extended until end 2022
- L2B wind product quality
  - Main bias sources understood and corrected, remaining bias close to requirement
  - Random error higher than required, but still allowing positive NWP impact
- L1B and L2B wind product publically released on 12 May 2020
- Significant positive impact reported by 8 NWP centers running global models
  - Largest in tropical upper troposphere and lower stratosphere and southern hemisphere
  - Regional models report modest but positive impact (expected from single-satellite demonstrator concept)
- Operational NWP assimilation
  - ECMWF, DWD, Météo-France operational. Starting soon: Met Office Dec 2020, Indian NCMRWF Q1 2021, JMA 2021
- Aeolus successfully demonstrate space-borne DWLs for accurate wind profiling
  - Interest to start programmatic steps for operational follow-on expressed by EUMETSAT Council and ESA Member States. Technological preparations started.

Thank you for your attention

Tropical Campaign – Airborne Fleet

Askos

OSCM
São Vincente

Sal

Light Aircraft

aero snemanje AEROVIZIJA

AVATAR-T

DLR

CADDIWA

SAFIRE

CPEX-AW

NASA

Potential Participation:

NOAA

FAAM