

AEOLUS-2 DOPPLER WIND LIDAR INSTRUMENT: STATUS UPDATE

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ABSTRACT

Aeolus-2 is the operational follow-on to the Aeolus demonstration mission and is being developed to provide sustained global wind profile observations for numerical weather prediction and climate applications. The mission baseline has evolved towards a single-satellite operational system in a sun-synchronous dawn-dusk orbit at approximately 450 km altitude, with a nominal operational lifetime of 5.5 years and an extension capability supported by consumables and design heritage. The Doppler Wind Lidar (DWL) Instrument builds on the heritage from the Atmospheric LASer Doppler INstrument (ALADIN) flown on the Aeolus satellite and ATmospheric LIDar (ATLID) flying on the EarthCARE satellite, while introducing a consolidated bistatic architecture, improved optical transmission, a higher-energy ultraviolet laser, enhanced co-alignment control, additional atmospheric channel, and a more robust design for an operational mission. This article summarizes the latest design updates, pre-development achievements, Laser Transmitter Assembly status, expected performance and remaining development outlook as the programme enters Phase B2/C/D.

Keywords: Aeolus-2, Doppler wind lidar, ultraviolet laser, atmospheric winds, co-alignment, lidar performance, pre-development, numerical weather prediction

1. INTRODUCTION

The DWL baseline has been consolidated to support an operational Aeolus-2 mission rather than a demonstration one. The current architecture is based on a single satellite, designed and qualified for a nominal operational lifetime of 5.5 years, with a realistic extension to 7 years based on ALADIN and ATLID heritage, ground test evidence, qualification approach and redundancy [1] [2] [3]. The mission is planned for an approximately 450 km sun-synchronous dawn-dusk orbit (18:00 LTAN) and is sized to provide Level-2 product timeliness compatible with operational meteorology needs, with 90% of the data targeted within 60 minutes and 100% within 120 minutes [4].

The instrument design has retained the bistatic architecture (ATLID heritage) selected during the initial design consolidation. This architecture separates the transmit and receive paths and supports a pressurized transmit chain, reducing the risks associated with laser-induced contamination and laser-induced damage on high-fluence ultraviolet optics. The transmit path includes two fully redundant chains comprising the Laser Transmitter Assembly (LTA), Beam Steering Mechanism (BSM), External Beam EXpander (EBEX) and baffle. The receive path reuses the 1.5 m ALADIN telescope concept with improved polishing, improved thermal control, and a Euclid-like baffle. The overall mechanical concept accommodates sensitive elements on a single isostatic carbon-fiber reinforced polymer baseplate to maximize thermo-elastic stability and preserve transmit-receive co-alignment.

The updated instrument includes three science channels and a Co-Alignment Sensor (CAS). The Mie channel supports wind retrieval in aerosol and cloud scenes, the Rayleigh channel supports molecular wind retrieval, and the cross-polar channel provides additional aerosol and cloud information. The Co-Alignment Sensor measures the atmospheric backscatter image of the ultraviolet beam and assures the closed-loop control of the Beam Steering Mechanism. The information provided by the CAS will also be used on ground to correct bias contributions linked to variations on the angle of incidence and the beam divergence. The functional architecture has also been consolidated. A redundant control electronics unit interfaces with the platform and hosts the instrument software, including autonomy, commandability and

fault detection, isolation and recovery functions. The redundant laser subsystem includes the Power Laser Head (PLH), Reference Laser Head (RLH), Laser Beam Monitoring Device Assembly (LBMDA) and Transmitter Laser Electronics (TLE). The instrument power budget is of the order of 1200 W, and the science and monitoring data flow remains compatible with the platform data-handling allocation [5][6].

2. INSTRUMENT ACCOMMODATION

The DWL-Instrument accommodation is driven by the bistatic architecture, which physically separates the transmit and receive optical paths. This separation addresses one of the main limitations identified from ALADIN by isolating the high-fluence ultraviolet emission chain from the low-signal receive path. The resulting configuration reduces the exposure of critical optics to high laser intensity and supports a pressurized transmit path, thereby mitigating laser-induced contamination and laser-induced damage risks. The focal-plane elements remain exposed only to very low optical intensities, further reducing lifetime and contamination risks.

The accommodation concept (Figure 1) places the transmitters, beam expanders and the receiver telescope with its focal plane on a common Bi-static Optical Assembly Structure (BOAS). This common bench limits thermo-elastic distortion and preserves the relative stability of the transmit and receive lines of sight. The receiver uses a 1.5 m Cassegrain telescope and a focal-plane assembly including the internal calibration path, filtering and beam-expansion optics, Mie and Rayleigh spectrometers, cross-polar detection chain, CAS and associated detector assemblies. The transmit path accommodates the nominal and redundant Laser Transmitter Assemblies, as well as the Magnified Aperture & Mechanism Beam Assembly (MAMBA) that is composed by the BSM and the EBEX. The transmit path is designed in a pressurized configuration.

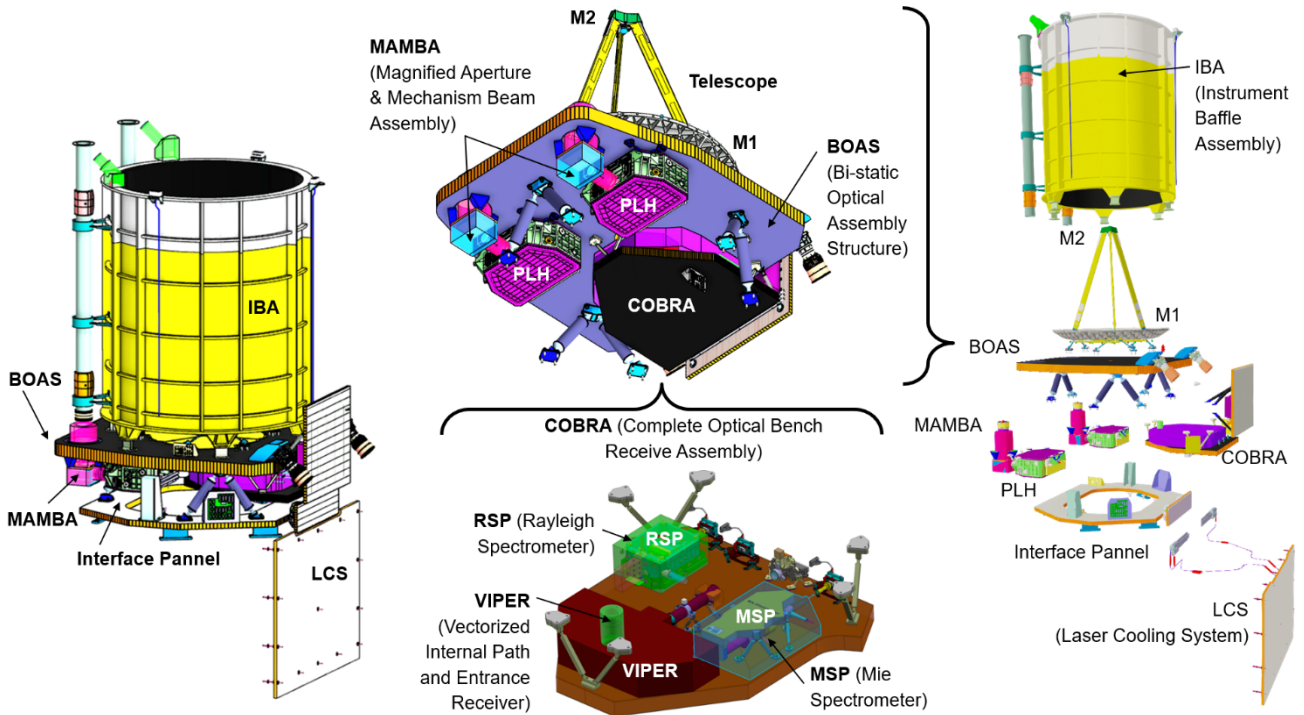


Figure 1: DWL accommodation and exploded views

The main accommodation drawback of the bistatic concept is the need to maintain accurate transmit-receive co-alignment. The Aeolus-2 DWL instrument mitigates this through mechanical stability and active control. The Co-Alignment Sensor observes the received image of the emitted ultraviolet beam and provides the signal used by the instrument computer to command the Beam Steering Mechanism. The same sensor information also will be used for ground processing corrections for incidence and divergence effects, which are more critical for Aeolus-2 because the emitter aperture is smaller than the receiver aperture.

The accommodation also incorporates ALADIN lessons learned on optical throughput, thermal stability and robustness. The primary mirror polishing and coating are controlled to reduce scattering losses, the thermal control of the primary mirror is improved to limit wavefront error, and the blocking-filter diaphragm is sized to avoid beam clipping under thermo-elastic distortion. Single-point-failure mechanisms used in ALADIN, such as the laser chopper and flip-flop mechanisms, are not necessary due to the bistatic configuration, increasing the robustness of the operational instrument baseline.

3. PRE-DEVELOPMENT STATUS

The Aeolus-2 pre-development programme has addressed the principal technical risks before entry into full development [7]. Activities have covered the laser transmitter, detectors, beam expander, beam steering mechanism and spectrometers. These activities were carried out in parallel with the Phase A/B1 studies and the instrument consolidation study, enabling the design baseline to be supported by breadboard results, subsystem characterization and updated performance simulations.

The Emission Beam Expander (EBEX) is a sealed and pressurized optical unit located in the transmit chain. It expands the high-energy laser beam delivered by the Laser Transmitter Assembly and accommodates the beam-tilting function required to co-align the emitted beam with the receive path. The required beam expansion leads to an exit beam diameter of up to 120 mm, thereby reducing the output divergence to the level required by the Aeolus-2 observation geometry. The EBEX design relies on several critical technologies, including stable mounting of large optical lenses, low wavefront error, high-fluence optical coatings, and hermetic sealing of a large-volume housing to enable pressurization and mitigate the risk of laser-induced contamination. Two activities run in parallel by OHB (Germany) and SENER (Spain) are now finalized and increased the level of maturity of the most critical functions.

The Beam Steering Assembly (BSA) provides the active transmit-beam pointing capability. It comprises the Beam Steering Mechanism, the Beam Steering Mechanism Electronics (BSME), and the Beam Steering Mechanism Harness (BSMH), which connects the mechanism to its electronics. Two parallel pre-development activities have been performed under the responsibility of CSEM in Switzerland and OHB in Germany to mature the key design functions.

The Aeolus-2 bistatic mechanical architecture has some changes compared to the one implemented for ATLID. In the current baseline, the BSM is accommodated within the EBEX cavity. This configuration provides a compact transmit-chain architecture but introduces additional design constraints for both units. For the EBEX, the integration of the BSM increases the number of electrical interfaces within the pressurized cavity and requires careful control of additional potential contamination sources. For the BSM, the architecture requires a larger steering mirror while maintaining stringent wavefront-error performance.

The EBEX and the BSA will be part of the MAMBA sub-assembly for the DWL Instrument.

For the pre-development of the spectrometers a Dual field compensated Michelson Interferometer (DMI) was selected as it had the potential to significantly reduce the sensitivity to angular misalignments. However later studies revealed a higher sensitivity to Mie cross contamination signal with respect to the current baseline that is the Double Edge Fabry-Perot (DEFP) based on the ALADIN heritage. Those activities were performed by TAS (Switzerland) and STI (Germany). The contract also included the development of the Fizeau for the Mie signal channel (also from ALADIN heritage).

The detector is a custom charge-coupled device developed by Teledyne e2v in the United Kingdom, referred to as the Accumulation CCD (ACCD). The Aeolus-2 ACCD builds on the heritage of the detector implemented in the ALADIN instrument, while providing enhanced functionality and increased sampling capability. The detector images the incoming laser return signal and, through successive charge transfers, accumulates on chip an atmospheric column profile averaged over the selected number of laser pulses. The vertical resolution of the retrieved profile is defined by the number of ACCD storage pixels, corresponding to the instrument range bins.

Several ACCD features are critical to meeting the demanding instrument performance requirements. These include low-noise charge transfer and on-chip accumulation, high-speed transfer of the image signal to the storage pixels, and low-noise readout of the previous atmospheric column sample during acquisition of the current sample. This operating concept enables efficient temporal averaging while preserving low readout noise.

The Aeolus-2 detector design introduces a larger image area, higher vertical resolution, and a dedicated image readout mode. In addition, design modifications have been implemented to mitigate limitations observed during the ALADIN in-

flight lifetime, in particular the occurrence of hot pixels [8]. The nominal operating temperature has also been reduced from -30 C degrees of ALADIN to -50 C degrees in order to the impacts of “hot” pixels (those pixels which develop higher background signal due to radiation as observed on ALADIN). .

The pre-development results confirm that the main technology selections are sufficiently mature to enter Phase B2/C/D with reduced risk. The bistatic architecture, pressurized transmit path and co-alignment loop have been consolidated by combining ATLID design heritage with ALADIN lessons learned. The receiver design has been updated to address ALADIN in-flight limitations, including optical throughput losses, telescope thermal sensitivity, polarization effects and straylight. The telescope primary mirror polishing and coating control, improved thermal regulation, larger blocking filter aperture and reduced stress in birefringent optics are key contributors to the updated link budget.

4. LASER TRANSMITTER ASSEMBLY

The Laser Transmitter Assembly is one of the major design drivers for Aeolus-2. The higher orbit altitude, bistatic architecture, lower divergence requirement, operational robustness objective and extended lifetime all impose more demanding requirements than those applied to ALADIN [9]. The Aeolus-2 pre-development activity therefore targeted ultraviolet pulse energy above 150 mJ (compared with an average of 60mJ for Aeolus), controlled beam divergence, an enlarged ultraviolet beam and improved stability over thermal and lifetime conditions.

The pre-development laser transmitter, manufactured by Leonardo, applies ALADIN and ATLID lessons learned. The design uses a master-oscillator power-amplifier diode-pumped solid-state Nd:YAG architecture based on Q-switching and frequency tripling to 355 nm. The Master Oscillator is thermally and mechanically separated from the amplification section to improve stability. The structure is pressurized to avoid air-to-vacuum transition effects and reduce laser-induced contamination phenomena. The ultraviolet section has been redesigned with enhanced harmonic crystals, improved beam shape control to increase conversion efficiency, and final beam expansion to decrease the divergence.

The characterization campaign demonstrated more than 350 mJ before the infrared beam expander and more than 160 mJ before the ultraviolet beam expander. The ultraviolet output showed a very low divergence far-field pattern, with measured divergence around 50 μ rad. These results are consistent with the Aeolus-2 requirement envelope and represent a substantial improvement compared with the Aeolus in-flight emitted energy levels.

Thermal sensitivity tests showed improved behavior compared with ALADIN and ATLID in key areas. The ultraviolet energy sensitivity is better than ALADIN, although slightly less favorable than ATLID because of the higher amplification level. Divergence stability along the amplifier cooling direction is significantly improved, and the Master Oscillator energy remains very stable over temperature. Non-operative thermal cycling did not introduce significant Master Oscillator beam centroid displacement, and the long-term test showed a flat energy evolution after initial mechanical and thermal stabilization. Detailed results of the long-term stability test are reported in Figure 2: the figure compares the energy evolution and MO beam position (horizontal and vertical) with similar on-ground tests performed on the lasers onboard ATLID and Aladin instruments, showing very good results.

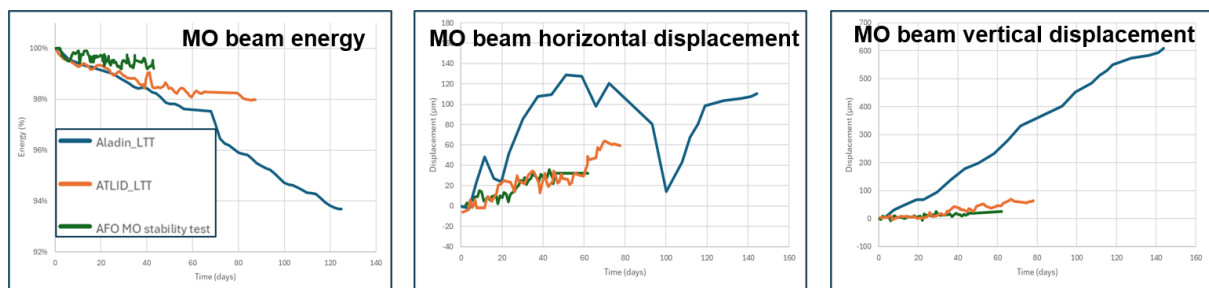


Figure 2: Results of the pre-development stability test on the LTA MO

On this basis, the Master Oscillator mechanical and radiometric stability is assessed as equivalent to, or better than, ATLID ground long-term-test performance and approximately five to ten times more stable than ALADIN. The pre-development

activity therefore achieved Technology Readiness Level 5 for the Power Laser Head and Technology Readiness Level 6 for the Master Oscillator section. The Aeolus-2 Phase B2 activities consequently start from a mature LTA baseline, which is a major risk-reduction achievement for an operational ultraviolet lidar mission.

5. PERFORMANCE

The expected Aeolus-2 performance benefits from the combined effects of higher emitted energy, improved transmit and receive optical transmissions, enhanced thermal stability, an increased number of vertical bins, and finer horizontal and vertical resolutions. These updates provide an estimated signal gain of approximately a factor of 4, resulting in a Signal-to-Noise Ratio (SNR) gain of approximately 2 relative to ALADIN, despite the increase in mean orbit altitude from 320 to 450 km.

Compared to Aeolus, the number of vertical bins increases from 25 to 67, and the vertical resolution is configurable from 0.125 to 5 km depending on the scene and SNR (rather than 0.25–2 km). Consequently, the vertical coverage extends from 0 to 40 km, up from 0 to 30 km. The onboard acquisition is capable of providing individual measurement profiles from a minimum of 10 accumulated pulses (1.5 km) with further accumulation performed during ground processing.

Aeolus-2 performance requirements are summarized in Table 1. The values reflect an operational mission requirement across vertical domains. The Mie and Rayleigh channels are designed to be complementary. The Rayleigh channel provides the best performance in cases of molecular (Rayleigh) scattering under clear-sky conditions, while the Mie channel performs best in cases of particulate (Mie) scattering from aerosols and clouds. For performance analyses, a horizontal integration length of 100 km is used for Rayleigh and aerosol scattering scenarios. In cloudy conditions, such as cirrus, cumulus, and stratus, the Mie channel can be used with a shorter 10 km integration length, provided the Scattering Ratio (SR) is sufficiently high.

Table 1: Random error and residual bias requirements across vertical domains.

Vertical Domain	Altitude (km)	Vertical Resolution (km)	Horizontal Integration Length (km)	Random Error (m/s)	Residual Bias at L1 (m/s)
PBL	0 – 2	0.5	100	2.0 (Mie) / 5.0 (Rayleigh)	0.9 (Mie) 1.7 (Rayleigh)*
Troposphere	2 – 14	1.0	100	2.5 (Rayleigh)	
	14 – 16			2.8 (Rayleigh)	
Lower Stratosphere	16 – 26	2.0	200	5.0 (Rayleigh)	
	26 – 30			6.0 (Rayleigh)	
Stratosphere	30 – 40	-		-	

* Including a scene-dependent bias of 1.0 m/s from Mie cross-talk and Temperature and Pressure effects (Rayleigh-Brillouin), to be corrected at L2.

Figure 1 shows the expected random error as a function of altitude evaluated for combinations of typical case (TC), worst-case (WC), beginning of life (BOL), and end of life (EOL). In all cases, the expected random error remains below the requirement across the entire vertical range with sufficient margin, providing a high level of confidence ahead of the development phases. Although the vertical coverage extends to 40 km, no random error specification is defined for the stratosphere (30–40 km). Performance in this region is therefore assessed relative to the performance in the lower stratosphere.

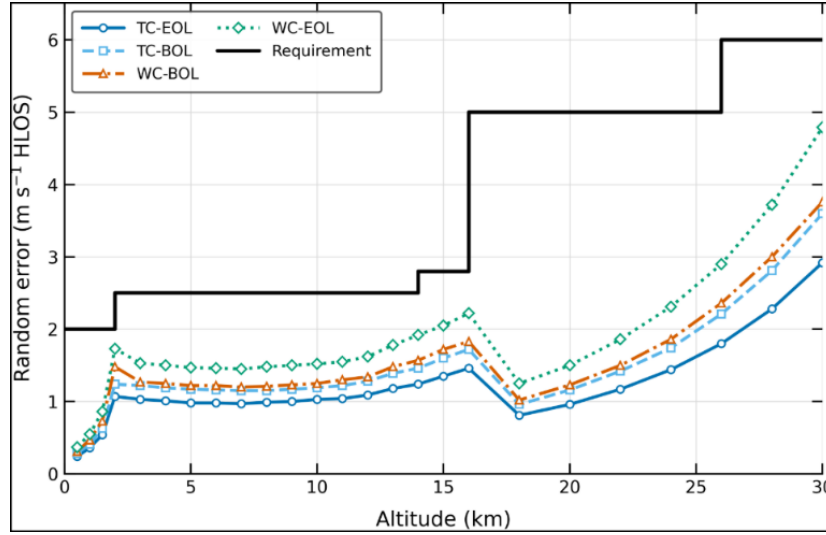


Figure 1: HLOS random error evaluated for different scenarios.

The residual bias budget separates native instrument and satellite biases from processing-correctable effects. At Level 1 (L1), the current specifications are 0.9 m/s for the Mie channel and 1.7 m/s for the Rayleigh channel. For the Rayleigh channel, the budget includes a scene-dependent bias (Rayleigh-Brillouin and Mie cross-talk) of approximately 1.0 m/s, which is to be corrected at Level 2 (L2). The expected residual biases at L1 are approximately 0.5 m/s and 1.6 m/s for the Mie and Rayleigh channels, respectively. After correction at L2, the expected residual bias for the Rayleigh channel is 0.6 m/s, while the Mie channel performance remains similar to that at L1. The main contributors to the residual bias include uncertainties in angle-of-incidence (AoI) and divergence corrections, zero-wind bias (ground echoes), slope errors, and platform-induced effects. Uncertainties in the AoI and divergence corrections are expected to be the largest contributors to the residual bias budget, particularly for the Rayleigh channel – based on the DEFP. Therefore, the quality of CAS measurements is crucial for correcting these bias terms.

Further performance improvements are being investigated, such as optimizing the slant angle (increasing it beyond the current 35° baseline) to enhance HLOS sensitivity, and reducing the Field Stop (FS) diameter to minimize solar background. Additionally, machine-learning techniques for HLOS wind retrievals and anomalous pixel detection are being explored. Early results indicate performance comparable to conventional retrieval methods at sufficiently high SNR, and significantly better performance under low-SNR conditions. A hybrid approach may therefore increase the number of usable wind retrievals and improve robustness against detector anomalies, including those potentially affecting the CAS.

6. CONCLUSIONS

Aeolus-2 has progressed from mission concept and technology risk reduction towards a consolidated operational Doppler Wind Lidar baseline. The current design combines Aeolus ALADIN heritage and flight experience, ATLID architectural heritage and flight experience, and a number of important dedicated Aeolus-2 pre-development results. The resulting instrument introduces a more robust bistatic configuration, a pressurized and redundant transmit path, improved receiver throughput, enhanced thermal control, additional atmospheric sensing capability, a dedicated co-alignment loop and a processing concept able to address incidence- and divergence-driven bias terms.

The Laser Transmitter Assembly pre-development is one of the strongest maturity indicators for the programme. The demonstrated ultraviolet energy above 150 mJ, low divergence, improved Master Oscillator stability, successful thermal characterization and achieved TRL status provide a mature starting point for Phase B2/C/D. This represents a major advance relative to previous ESA ultraviolet lidar developments and directly supports the operational lifetime and performance objectives of Aeolus-2.

The performance analysis shows that Aeolus-2 will meet all mission requirements with sufficient margin, providing high confidence ahead of the development phases. The combination of improved signal performance, extended vertical coverage, and continued optimization efforts ensures that Aeolus-2 will advance global wind observation capabilities well

beyond those achieved by the Aeolus mission. The updated link budget, improved optical transmission, larger vertical sampling capability and bias correction strategy support the transition from the Aeolus demonstrator to a long-term operational mission. The remaining Phase B2/C/D activities shall consolidate the detailed design, verification approach, calibration strategy and processor implementation while preserving the performance margins demonstrated during pre-development.

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