

The emission beam expander for AEOLUS-2: Pre-development results

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ABSTRACT

The pressurized emission beam expander is a key subsystem of the AEOLUS-2 Doppler Wind LiDAR. Its primary function is to expand the outgoing UV laser beam, ensuring minimal beam divergence while preserving the wavefront. The spatially separated emission and reception paths are a core element of the new bi-static instrument architecture of AEOLUS-2. It features a pressurized emission path making use of ozone cleaning to prevent laser-induced contamination formation and transmissive optics with high laser-induced damage threshold. These technical aspects were identified to be critical to the functioning and performance of the system. Within the framework of a pre-development activity carried out at OHB System AG, this paper presents the main challenges and critical technologies of the emission beam expander together with the results of the test campaign. The design, analysis, and testing of the breadboard are detailed in the following.

Introduction

AEOLUS-2 is a planned UV Doppler Wind LiDAR building on the success of the AEOLUS demonstrator mission^{1,2}. The mission is funded by ESA and Airbus was awarded the contract for its development in 2026. It will contribute to improving weather forecasting by measuring wind profiles³. Due to the challenges posed by Laser-Induced Contamination (LIC) in the high-power emission path⁴, a bi-static architecture with spatially separated transmit and receive optical paths is foreseen. This design is based on the proof-of-concept instrument ATLID, flown on EarthCARE^{5,6}. To further mitigate the risk of LIC and ensure long-term optical performance, dense optical coatings, high-quality optical components, and a pressurized compartment with an oxygenated atmosphere are employed. The bi-static architecture requires the minimization of the divergence of the emitted beam, using a thermal defocus feature. In addition, the transmit and receive Lines of Sight (LoS) must be co-aligned using a Beam Steering Mechanism (BSM), subject of a separate pre-development activity undertaken by OHB and CTEC.

The EBEX design is driven by envelope and mass constraints in conjunction with stringent optical performance requirements. To mitigate technical risks, critical technologies were identified: stress-free optics mounting, high-performance anti-reflective (AR) coating, high quality optics, thermal focusing control, and the achievement of an inorganic hermetic sealing for the pressurized compartment. The objective was to advance each technology to Technology Readiness Level⁷ (TRL) 5. Initially, these technologies were assessed at TRL 3 or less.

A flight-representative breadboard was designed, manufactured, aligned, and tested during the project. The opto-mechanical and thermal performance met the requirements due to dedicated optimization methods. The environmental and performance tests demonstrated the success of this activity by exceeding expectations, with all technologies reaching TRL 5 or 6.

Design

Optical Design

The optical layout of the EBEX relies on a dioptric afocal telescope. The Galilean-type telescope (negative-power lens group followed by positive-power lens group) was selected because of its compactness and the absence of an intermediate focus. The best option identified to balance performance and weight was a three-singlet system. The negative lens group is composed of a biconcave spherical lens (L1) and a plano-concave spherical lens (L2). The positive lens group consists of one plano-convex aspheric lens (L3), whose aspheric surface is needed to achieve improved nominal performance. The EBEX is housed in a pressurized compartment closed by a sealed exit window (WEx). For the flight model, the housing also includes a Beam Steering Mechanism (BSM) and an entrance window which were not part of the breadboard model. The entrance pupil is placed at the BSM level and has a diameter of 30 mm.

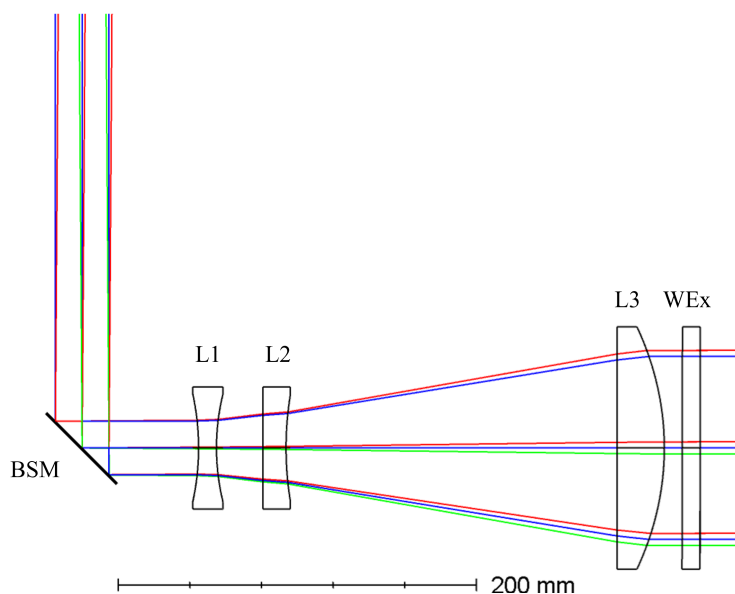


Figure 1. EBEX optical design. The BSM is represented but not part of the pre-development.

The Field-of-View (FoV) is square and equal to $0.4^\circ \times 0.4^\circ$. The optical design is optimized for a wavelength of (354.80 ± 0.03) nm, and the nominal magnification is 3.4. The lenses and exit window are manufactured from high-purity fused silica and coated with dense dielectric AR coatings. High purity fused silica was selected due to its high transmission in the ultraviolet range, low levels of bubbles and inclusions, and low intrinsic birefringence.

Mechanical design

The EBEX mechanical design (without the BSM) consists of several subassemblies, as shown by the exploded view in Figure 2.

The pressure-tight enclosure is formed by a Titanium housing and several flanges with leak-tight inorganic seals. These ensure compliance with the leak-rate requirement ($<2.7 \times 10^{-7}$ mbarLs⁻¹) over the complete temperature range until end-of-life (EoL). This requirement is driven by the allowable defocus drift towards EoL and the need for an oxygenated atmosphere. Electrical feedthroughs are implemented using e-beam welded connectors with an internal leak rate suitable for the application.

Each optical element is housed in a dedicated grade-5 titanium mount bolted to the titanium housing. It also incorporates flexures to accommodate radial thermal expansion. The lenses are glued to invar pads, which are in turn glued to the titanium mount in order to minimize mechanical stress in the lenses. The adhesive was prepared and cured according to a procedure from ATLID heritage. Six invar bonding pads are used for L1 and L2, whereas the larger L3 requires twelve. The pads provide a good coefficient of thermal expansion (CTE) match to the fused

silica substrate of the optics. Two heaters, positioned on the housing around the L1/L2 assembly and the L3 element, enable active thermal control of the defocus. The resulting spatially inhomogeneous temperature field generates both deformations and refractive index variations, used to tune the defocus.

The exit window is mounted to an invar flange. Low radial stiffness is achieved through an integrated element joined by laser soldering. The mismatch in thermal expansion between invar flange and titanium housing is resolved by using an all-metal sealing (Helicoflex type). This sealing is commonly used in application with ultra-high vacuum conditions and large temperature variations.

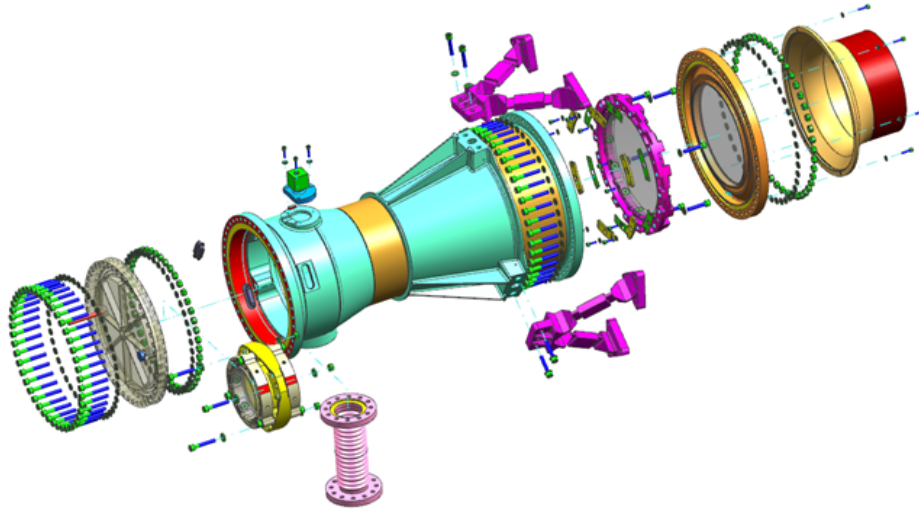


Figure 2. EBEX breadboard exploded view

Nominal performance

The nominal WFE and defocus values are given in Table 1 for the central wavelength and the limits of the wavelength band.

Table 1. Nominal WFE (without piston/tip/tilt/defocus) and defocus values of the EBEX.

	354.77 nm	354.8 nm	354.83 nm
WFE without defocus (nm RMS) - FoV = (0°,0°)	0.66	0.72	0.79
WFE without defocus (nm RMS) - FoV = (0.4°,0.4°)	2.32	2.3	2.29
Defocus (nm RMS) - FoV = (0°,0°)	10.51	2.59	-5.33
Defocus (nm RMS) - FoV = (0.4°,0.4°)	5.14	-2.82	-10.72

The Full-Field Displays (FFD) of the nominal WFE (without piston/tip/tilt/defocus) and the defocus for the central wavelength are given in Figure 3.

Alignment philosophy

The L1/2 assembly was aligned using a CMM. Axial alignment was performed via metal foil shimming; lateral alignment was implemented using bolting holes and differential micrometers. L3 was integrated next: its lateral translations were used to minimize higher-order WFE, its axial shimming to reduce defocus. For the flight model, an intentional defocus could be introduced at 20°C to meet the defocus tuning range requirement. For a fine alignment, residual defocus may be removed by varying the internal pressure rather than iterative fine shimming.

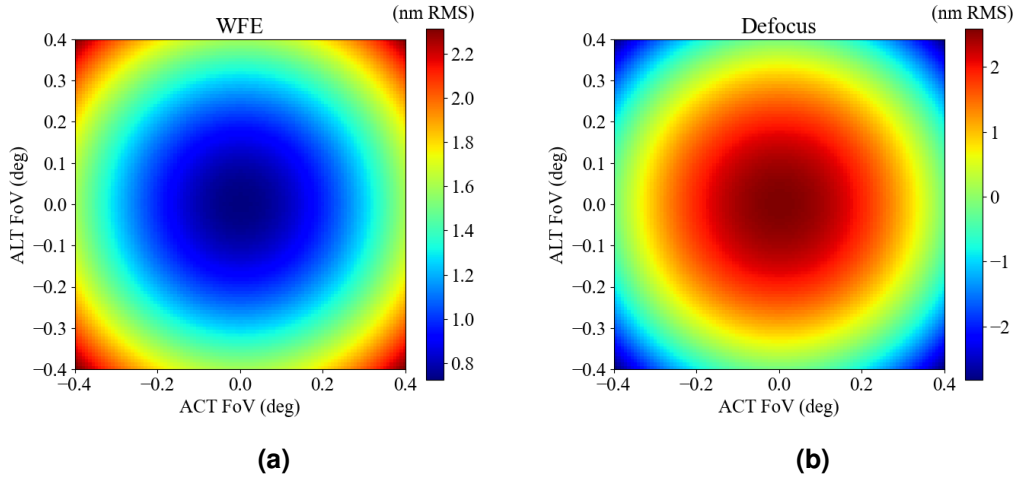


Figure 3. a) Full-Field Display reporting the RMS value (in nm) of the nominal WFE without piston/tip/tilt/defocus across the FoV at 354.8 nm. b) Full-Field Display reporting the RMS value (in nm) of the nominal defocus across the FoV at 354.8 nm.

Experimental setups

Wavefront error, LoS and magnification measurement setup

The WFE measurement was performed as an end-to-end optical verification of the EBEX breadboard. The wavefront was measured in double pass, using a Phasics wavefront sensor with four-wave lateral shearing interferometry. A sketch of the setup is shown in Figure 4.

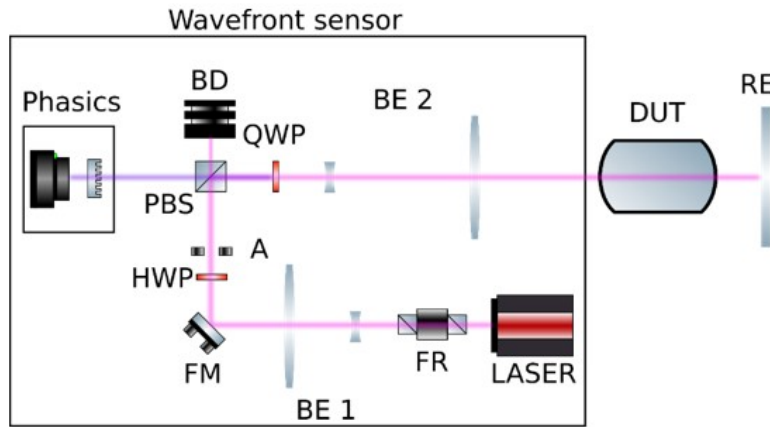


Figure 4. Sketch of the custom WFE measurement setup with pupil relays doubling as beam expanders. BE 1: Beam expander, FR: Faraday rotator (optional), FM: Folding mirror, HWP: Half-wave plate, A: Aperture stop (homogenizer), PBS: Polarizing beam splitter, QWP: Quarter-wave plate, BE 2: Beam expander for matching illumination, Phasics: UV WFS (matrix detector with micrograting array), BD: Beam dump, DUT: Device under test, RE: Reference mirror.

The wavefront distortion introduced by the relay optics and source was measured and subtracted from the measured EBEX WFE. The stability of the measurement setup was in line with the experimental needs, with a reproducibility over 10 hours of better than 2 nm.

The LoS measurement was performed to quantify the angular pointing direction of the EBEX optical axis using the same setup as that used for the WFE measurement. As the relay, beam expansion optics and micrograting array

of the wavefront sensor are expected to exhibit an imperfect and unknown LoS, a calibration measurement was performed using a corner cube reflector (CCR).

Measurements were repeated after integration, thermal testing, and vibration/leak testing to assess both the absolute optical performance and the stability under environmental exposure.

The magnification test was performed to verify the optical magnification of the beam expander, using the same setup previously described. The measurement relied on introducing a precisely known angular tilt to the reference mirror and recording the corresponding angular change measured by the wavefront sensor. By comparing the applied and measured angular deviations, the magnification factor of the EBEX was determined directly. The magnification of the WFS and relay optics was measured in advance and corrected for. Results are presented in the subsection "Wavefront error, LoS and magnification measurements".

Depolarization assessment

The polarization requirement is defined in terms of the depolarization ratio, which is the power ratio of the perpendicular linear polarization (oriented at 90° to the incident polarization direction) to the parallel linear polarization (oriented along the incident polarization direction). The definition assumes a perfectly linearly polarized incident beam.

The depolarization performance was assessed through a polarization budget combining optical modeling, stress analysis, and birefringence measurements of the mounted optics. Measured stress after integration in the lenses and the exit window was compared with analytical predictions. The polarization change introduced by stress-induced birefringence was then analytically quantified. Results are presented in the subsection "Depolarization measurements".

AR coating performance testing

A qualification process was carried out for the coatings, which constituted a delta qualification with respect to the previous coating heritage (AEOLUS). The test philosophy was based on the ECSS-Q-ST-70-17C⁸ and ISO 9211 standards⁹. A set of flat coating process samples was procured by the lens and window optics supplier and coated by the coating supplier. Coated witness samples representative of the flight optics were subjected to spectral transmission measurements, humidity exposure, thermal-vacuum cycling, atomic oxygen exposure, cleaning tests, abrasion testing, and adhesion testing. Optical performance was measured before and after each environmental test. It was verified that the coating retained its transmission and reflectivity characteristics and showed no signs of degradation. Results are presented in the subsection "AR coating performance".

LIC and LIDT testing

LIC and LIDT tests were performed by DLR Stuttgart. The LIC test evaluated the susceptibility of the optical coating to contamination-related degradation under ultraviolet laser irradiation. The optic was irradiated in a controlled atmosphere (25% O_2 / 75% N_2 at 1 bar) while transmission and fluorescence were monitored. Any contamination growth would appear as increased fluorescence and/or transmission loss. Post-test microscopy was used to confirm deposit formation.

The LIDT campaign assessed the maximum laser fluence the coated optics can withstand without damage. The optic was irradiated with repeated UV laser pulses (355 nm) at increasing fluence levels, and damage was detected through in-situ scattering measurements. Results are presented in the subsection "LIC and LIDT test results".

Leak testing

The leak test was performed to verify the hermeticity of the pressurized EBEX cavity. This ensures that the defocus stability over the nominal instrument lifetime due to depressurization is met. LIC is prevented thanks to ozone cleaning¹⁰. A He-leak test was performed inside a TVAC chamber (see Figure 5). The unit was evacuated, repressurized with helium, and placed in a vacuum environment connected to a helium mass spectrometer leak detector. Any helium escaping through seals, feedthroughs, or interfaces was measured as a quantitative leak rate. This is possible because only metal seals are used, which feature no permeation. Results are presented in the subsection "Leak test result".

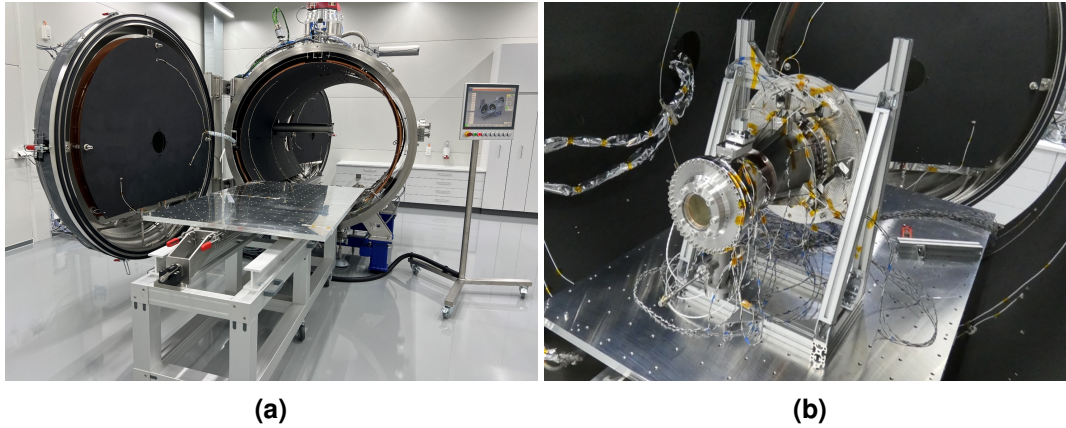


Figure 5. a) TVAC at OHB premises. b) EBEX inside the TVAC chamber.

Vibrational testing

The vibration test simulated the launch environment and verified the structural integrity and optical stability of EBEX. The unit was mounted on a shaker adapter, providing a stiff interface to the shaker via its bipods. The EBEX was then subjected to qualification-level sine and random vibration loads along all three axes (see Figure 6). Low-level resonance searches were performed before and after each qualification run to detect any structural changes or damage. Post-test optical measurements allowed verification that the unit maintained its functionality without damage or performance degradation. Results are presented in the subsection "Vibration test result".

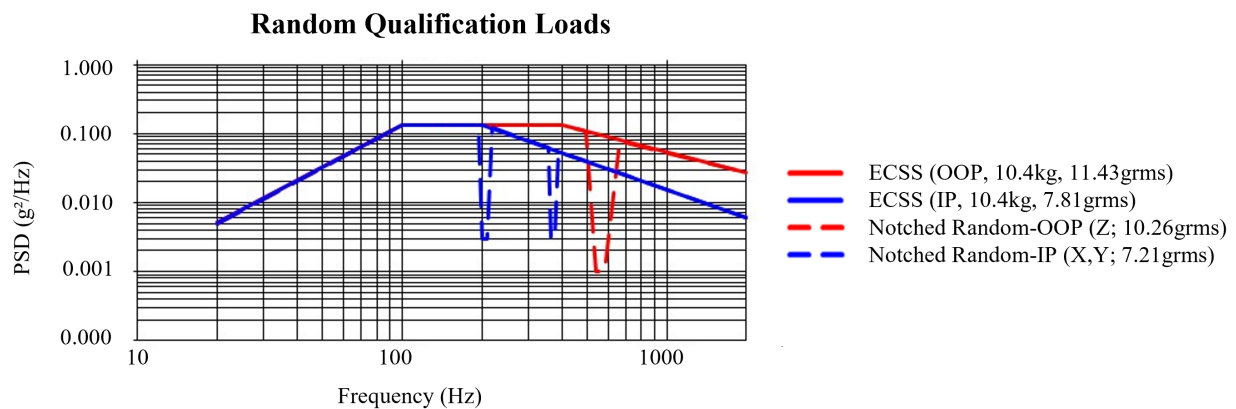


Figure 6. ECSS Random Loads applied to EBEX during the vibration test.

Thermal defocus function test

The thermal focus verification test demonstrated the capability of the active thermal defocus control system. The EBEX was placed in a thermal-vacuum chamber and the integrated L3-heaters were operated at different power levels. After thermal stabilization, the WFE was recorded. The correlation between the heater power and the measured temperature of L3 is shown in Figure 7.

Prior to testing, the WFE was predicted as a function of the power applied to the lenses using numerical simulations. A finite element model was implemented in ANSYS to capture the thermal and structural behavior of the system. The resulting temperature, stress, displacement, and deformation fields were exported to Zemax using the STAR module. The measured WFE was then compared with the WFE predicted by Zemax. Results are presented in the subsection "Thermal defocus function verification".

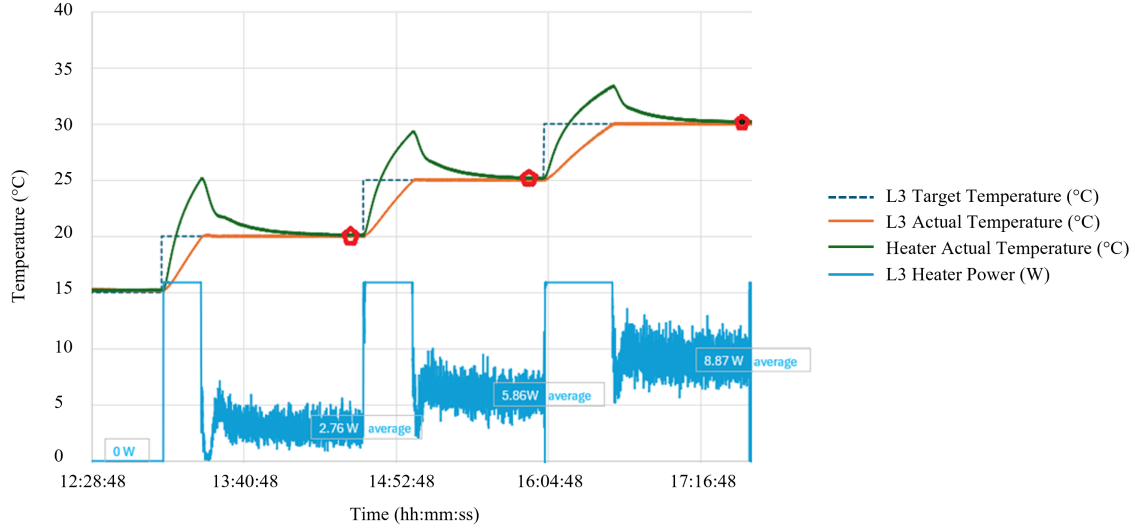


Figure 7. L3 and heater temperatures variation with input heater power. The blue curve shows the input power allocated to the L3 heater. The orange curve shows the L3 temperature, while the green curve shows the heater temperature. The dashed blue curve represents the L3 temperature target.

Results and discussion

Wavefront error, LoS and magnification measurements

The WFE characterization was performed throughout the test campaign and remained largely stable, increasing from 34 nm RMS after integration and alignment to 36.7 nm RMS after thermal testing and 40.7 nm RMS after vibration and leak testing (see Figure 8).

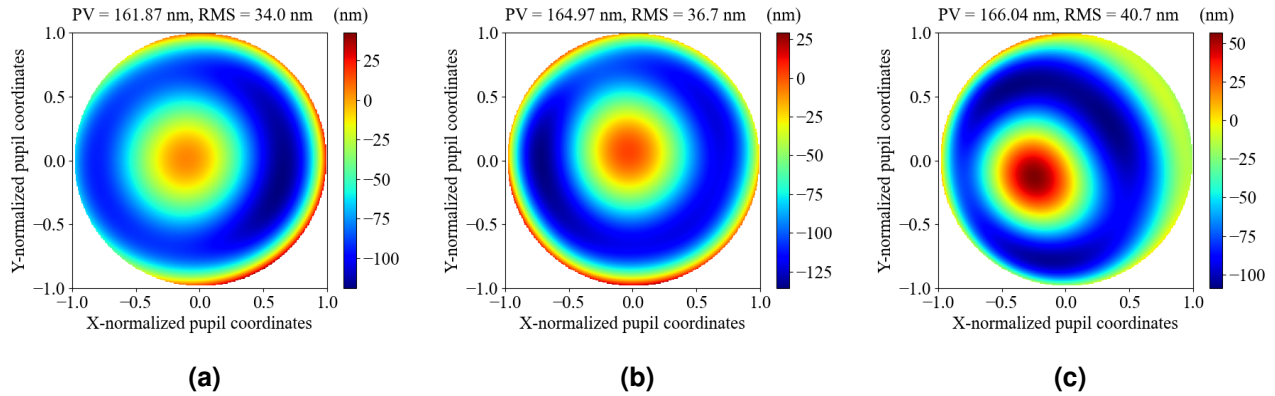


Figure 8. Measured WFE (without piston/tip/tilt/defocus) after integration and alignment (a), after thermal testing (b) and after vibration and leak testing (c). Values are given in nm.

The measured WFE did not meet the requirement of 25 nm RMS, primarily due to unexpectedly high stress introduced by the exit-window mounting, which contributed approximately 27.7 nm RMS to the overall wavefront error. In addition, a missing annealing step before final machining led to significant spherical aberration, contributing approximately 24 nm RMS across the complete EBEX assembly. Excluding this spherical aberration term, the total WFE would be reduced from 40.7 nm RMS to 32.9 nm RMS. The measured WFE, excluding this spherical aberration term, are shown in Figure 9.

The results motivated a redesign of the exit-window mounting concept to mitigate stress-induced aberrations in

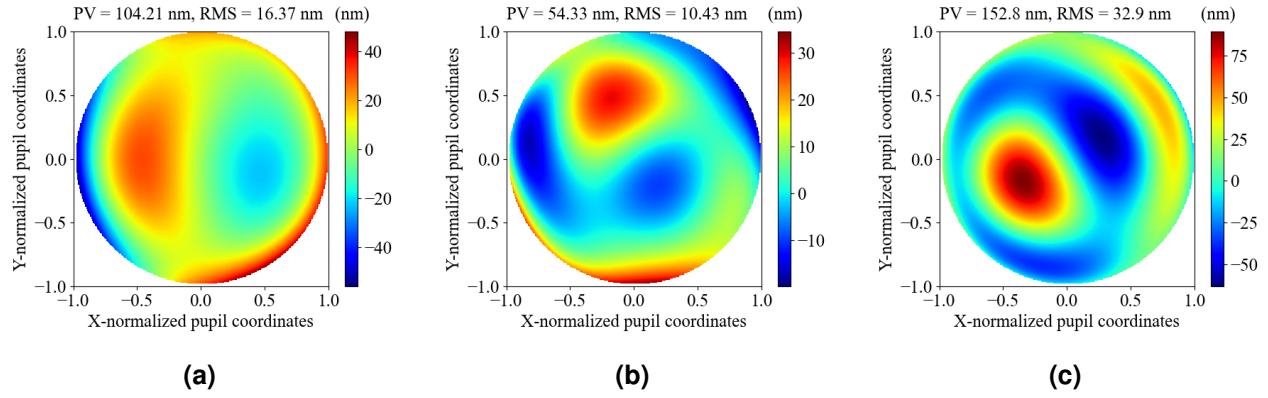


Figure 9. Measured WFE (without piston/tip/tilt/defocus) with spherical aberration removed (assuming the annealing step was performed) after integration and alignment (a), after thermal testing (b) and after vibration and leak testing (c). Values are given in nm.

the upcoming implementation phases. The test campaign also demonstrated excellent WFE stability, with a variation of only 7.3 nm RMS, meeting the 10 nm RMS requirement.

The LoS variation was measured after integration and again following the vibration campaign. A value of $96.7 \mu\text{rad}$ was obtained, remaining just below the specified requirement of $100 \mu\text{rad}$ and therefore demonstrating compliance. The magnification measurement also met the specified requirement, yielding a value of (3.39 ± 0.01) , which is well within the acceptance range of (3.40 ± 0.05) .

Depolarization measurements

The polarization budget was driven by the birefringence of the lenses and the exit window, induced by the mounting stress. The measured stress after integration (see Figure 10) was at least two times lower than the stress considered in the simulations performed by OHB and did not exceed 1.1 MPa. Based on the results from tests on the subassembly level, the analytically estimated depolarization ratio of 0.11% was thus well within the 0.5% requirement.

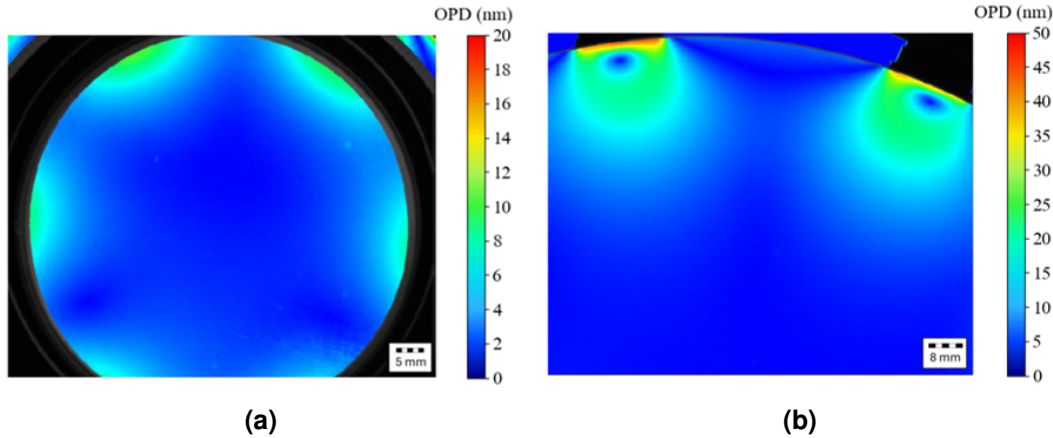


Figure 10. a) Stress-induced birefringence of L1 b) Stress-induced birefringence close to the glue pad of L3. The color scale corresponds to different values of optical path difference (OPD).

AR coating performance

Coating samples with a surface roughness of $\leq 1 \text{ nm}$ were used for the qualification. Transmission measurements in combination with model predictions were performed to evaluate the reflectivity. This served as the reference for

the samples that later underwent environmental testing. The reflectivity met the specification with a transmission exceeding 99.9% at normal incidence. The samples passed all the environmental tests without any degradation observed. The coating also successfully passed the LIC test with a representative amount of glue.

LIC and LIDT test results

Samples with a 1 nm surface roughness were tested initially. The LIC test was successful but micro-pits were created during LIDT testing. The initial LIDT test yielded a damage threshold of $(2.6 \pm 0.4) \text{ J cm}^{-2}$, exceeding the specified requirement of 2.4 J cm^{-2} . Damage at this threshold consisted primarily of small micron-sized pits (see Figure 11a), while significant coating degradation (see Figure 11b) occurred only at much higher fluences (7.6 J cm^{-2}). A second LIDT test performed on a super-polished sample (0.25 nm surface roughness) from the same coating run resulted in a significantly higher threshold of $(17.9 \pm 2.6) \text{ J cm}^{-2}$. The relatively low LIDT measured during the first LIDT test was attributed to the formation of micro-pits, which are likely caused by insufficient substrate polishing quality. After the second test, the LIDT test was considered successful: Therefore, super-polishing should be implemented at least for the small lenses.

The endurance test, performed over approximately 317 million laser shots at 1.2 J cm^{-2} , showed no measurable transmission degradation, although a small number of micro-pits were observed by post-test microscopy.

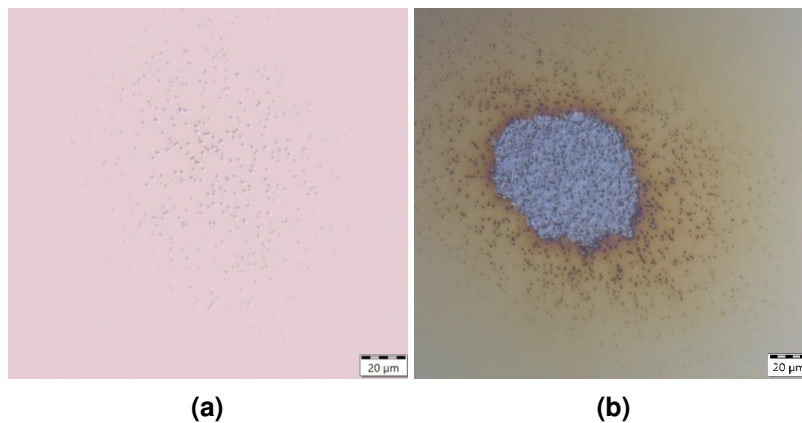


Figure 11. a) Example of micro-pit formation. b) Example of heavy damage of the coating.

Leak test result

The leak tests demonstrated excellent hermeticity of the EBEX assembly, with measured leak rates below $(<1 \times 10^{-7} \text{ mbar L s}^{-1})$ and a measurement sensitivity better than $(<1 \times 10^{-9} \text{ mbar L s}^{-1})$. Compliance with the leak-rate requirement was achieved through custom metal seals (Helicoflex-type seals manufactured by Technetics) and Swagelok connectors (used for the pressure sensor and pinch-off interfaces). To achieve hermeticity, a glue line was added on top of the laser soldering used to mount the exit window.

Vibration test result

Initial low-level sine tests verified that the measured stiffness of the structure matched the predicted eigenfrequencies. The first eigenfrequency of 211 Hz was measured to be well above the requested 180 Hz (see Figure 12). A quasi-static sine load of 40 g and the random qualification loads depicted in Figure 6 were then applied to demonstrate that the structure - especially the lenses and flexible lens mounts - would sustain the launch loads without any degradation of performance or functionality.

Thermal defocus function verification

An initial correlation between the thermal model and the experimental results was performed to determine key coupling factors, including contact conductances and emissivities. The defocus predictions, evaluated with the

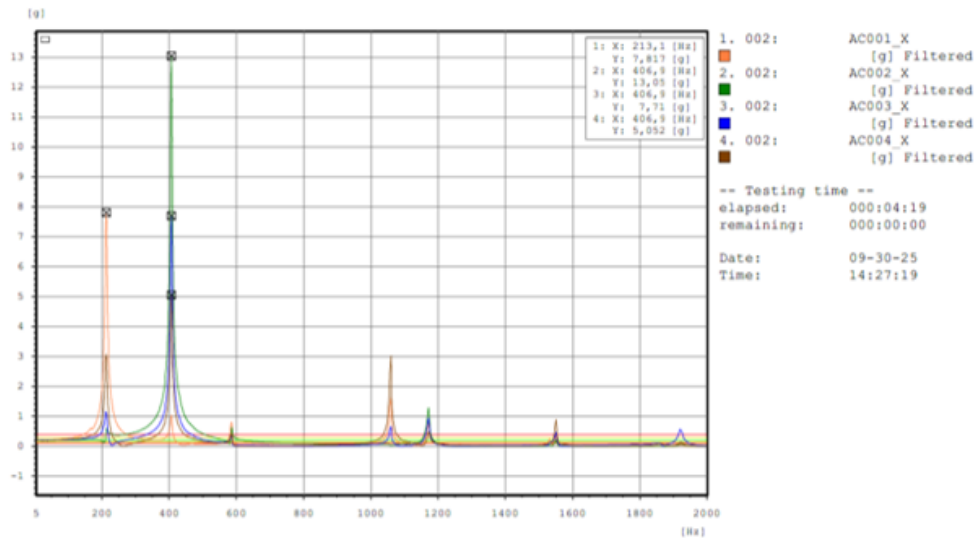


Figure 12. Resonance search (Low-Level sine up to 2000Hz).

STAR module, were in line with the measurement data within a 10% error margin (see Figure 13a). This strong correlation demonstrates the maturity of OHB's Structural-Thermal-Optical-Performance (STOP) analysis toolchain in accurately predicting the behavior of a system subject to multiphysics simulations. As a result, design risks can be significantly reduced in future developments, as validated simulation models can be employed to predict system performance and support design optimization.

The defocus tuning range requirement is ± 50 nm RMS across two operational temperature ranges: the cold case (CC) from -100°C to 46°C and the hot case (HC) from -15°C to 50°C . By applying a known defocus offset during alignment, the required tuning capability can be achieved with margin, within the allowed power range of 0 W to 4 W (see Figure 13b). This assumes that the initial alignment and defocus offsets can be established, which will likely require a minor adjustment to the EBEX internal pressure.

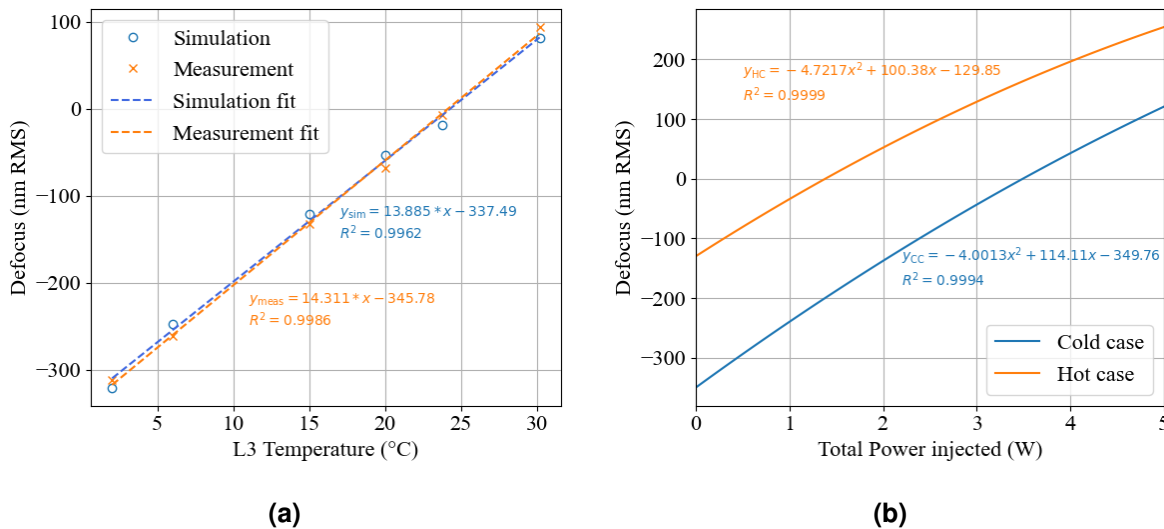


Figure 13. a) Correlation between defocus measurement and simulation for different temperatures of L3. Measured and simulated values fitted with a linear model. b) Defocus range achievable during Hot Case and Cold Case with respect to the power applied on L3. Measured values fitted with a second-order polynomial model on a higher power range (0 W-12 W)

Conclusion

During this pre-development activity, an EBEX breadboard representative of the flight design was designed, manufactured, and tested. The successful completion of the performance and environmental test campaign demonstrated the feasibility of the concept.

Overall, the critical technologies achieved a higher maturity level than initially targeted. TRL 6 was reached for all technologies except laser soldering as a stress-free mounting technology and the high-quality optics aspect for L3, both of which achieved TRL 5.

Furthermore, the successful correlation between thermal, structural, and optical analyses was essential for accurately predicting system performance and validating the modelling approach. A validated analysis chain will benefit any future development with similar functionality.

Overall, this activity represents an important de-risking step for the upcoming AEOLUS-2 implementation phase. It successfully demonstrated the maturity and overall feasibility of the EBEX concept while providing valuable lessons learned and recommendations for the subsequent development stages, regarding optics manufacturing, multiphysics modeling, and stress-free hermetic mounting techniques.

Looking ahead to AEOLUS-2 phases B2CD, the EBEX together with the BSM, will be part of the MAMBA subsystem¹¹, for which an ITT has been issued.

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