

OSTEELoS: a novel Telescope with $\pm 18.5^\circ$ steerable line of sight. Measurements campaign on the breadboard

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ABSTRACT

The paper presents the opto-mechanical design, the manufacturing, the integration phases and the optical measurements of a breadboard of the OSTEELoS Telescope. OSTEELoS is a 480 mm focal length novel telescope, working at F/6, with an extremely compact cross-section in the flight direction, with a main channel in the thermal infrared [8;14] μm and an auxiliary channel in the spectral range [400;1000] nm. The system is conceived to perform continuous videos from a VLEO orbit. The OSTEELoS telescope concept consists of two freeform powered mirrors M1 and M2 with no plane of symmetry. The field of view (FoV) is $\pm 0.055^\circ$ in the along track direction and $\pm 0.025^\circ$ in the across track direction. A freeform stabilization mirror stabilizes the image and slightly extends the FoV around the instantaneous field of view. A freeform Germanium beam splitter separates the visible from the thermal infrared channel. The aperture stop is at the entrance aperture. Nominal performances are diffraction-limited in the thermal infrared with a gentle degradation of the image quality in the visible channel. OSTEELoS concept changes the along track line-of-sight direction in the range $\pm 18.5^\circ$ with a continuous movement of the mirrors M1 and M2 in the along track direction. The design, relying on a modification of the Alvarez concept proposed by L. Maresi and T. Agócs, avoids the use of a scanning mirror to change the line-of-sight direction, thus facilitating an extremely compact design in the flight direction. The main aim of the breadboarding activity is to validate the design concept by continuously changing the along track line-of-sight within a wide range of $\pm 18.5^\circ$ while keeping the image quality almost unchanged. The mirrors and telescope housing are made of aluminum. In the breadboard, the beam splitter was manufactured in aluminum and only the visible channel was tested. The OSTEELoS breadboard was fully integrated, aligned and tested at OHB premises. Robustness of the optical design to manufacturing and integration tolerances was achieved in the design phase by means of the Helmholtz-Lagrange Invariant. This made possible to align the four freeform mirrors, lacking any symmetry, in few days only, using an interferometric cavity instead of a time-consuming CMM-aided approach. A supporting analysis using nodal aberration theory is also performed to interpret the results of the tolerance analysis and to establish the required high-degree of the alignment.

The measurement campaign consisted in measuring the WFE in across- and along-track for different discrete line-of-sight positions at 633 nm. The focal length was also measured. The MTF performance at 10 μm wavelength was determined by a combination of measurements and analysis. The OSTEELoS breadboard shows full compliance for wavefront error and focal length, representing a validation of this novel design concept and an important step towards a potential application in acquiring persistent videos from LEO. Furthermore, the OSTEELoS breadboard shows that complex optical systems without any plane-symmetry can be aligned relatively easily when the optical design relies on fundamental imaging conditions.

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Keywords: exotic design, freeform optic, Alvarez concept, WFE measurement, Helmholtz-Lagrange invariant, thermal infrared, nodal aberration theory, persistent videos.

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1. INTRODUCTION

The OSTEELoS Telescope can be defined – by rephrasing the words of Jose M. Sasian in [1] – as an exotic system providing a practical solution to a difficult problem. The system is conceived to perform continuous videos from VLEO.

In order to do so, the telescope needs a mechanism to scan the line of sight to continuously point to the area of interest while the satellite is orbiting over it. Furthermore, the telescope shall minimize the atmospheric drag.

These problems have been solved with the OSTEELoS design that is capable of continuously changing the along track line-of-sight (LoS) within a wide range of $\pm 18.5^\circ$ - while keeping the image quality almost unchanged - without a scanning mirror. Furthermore, the challenge that OSTEELoS must deal with is the achievement of a focal length of approximately 480 mm in a very compact cross section in the flight direction, while accommodating two spectral channels, a main thermal infrared one and an auxiliary visible one. The compact section in the flight direction allows OSTEELoS – thanks to a reduced atmospheric drag – to fly at very low Earth orbits (VLEO).

The two mentioned aspects, namely the continuously changing of the LoS with almost no image quality degradation and the compact cross-section in the in-flight direction, make OSTEELoS a good candidate for performing continuous TIR videos from a VLEO orbit.

2. TELESCOPE DESCRIPTION

OSTEELoS is a 480 mm focal length novel telescope, working at relative aperture F/6, with an extremely compact cross-section in the flight direction, with a main spectral channel in the thermal infrared [8;14] μm and an auxiliary channel in the visible spectral range [400;1000] nm. OSTEELoS is conceived to perform continuous videos from a VLEO orbit. Table 1 summarizes the main optical properties of the OSTEELoS Telescope.

Table 1 Main optical data of the OSTEELoS telescope.

Parameter	Value
Focal length in ALT at LoS 0° [mm]	488.0
Focal length in ACT at LoS 0° [mm]	489.1
Entrance Aperture [mm]	78.0
Field of View ALT x ACT $^\circ$	$\pm 0.055^\circ \times \pm 0.025^\circ$
VNIR spectral range [nm]	[400; 1000]
TIR spectral range μm	[8; 14]
Range of steerable LoS	$\pm 18.5^\circ$
M1 Travel range [mm]	± 125
M2 travel range [mm]	± 114

The Telescope consists of two freeform powered mirrors M1 and M2 with no plane of symmetry. The field of view is $\pm 0.055^\circ$ in the along track direction and $\pm 0.025^\circ$ in the across track direction. A freeform stabilization mirror SM aims to stabilize the image and to slightly extend the FoV around the instantaneous field of view. A freeform germanium beam splitter BS separates the visible channel from the thermal infrared channel. The first surface of the BS has a freeform shape to further correct the aberrations of the reflected visible channel, while the back surface is a flat surface. The aperture stop is placed at the entrance aperture of the telescope and it is shifted away from the common axis of M1 and M2 in the Y (=ACT) direction, making the system unobscured off-axis. The nominal performances are diffraction limited in the thermal infrared with a gentle degradation of the image quality in the visible channel.

OSTEELoS changes the along track line-of-sight direction in the range $\pm 18.5^\circ$ with a continuous movement of the main imaging mirrors M1 and M2 in the along track direction, that is in the flight direction. The design, relying on a modification of the Alvarez concept proposed by the co-authors of this paper L. Maresi and T. Agócs and named *Magócs*, avoids the use of a scanning mirror to change the line-of-sight direction resulting extremely compact in the flight direction.

The optical design of the OSTEELoS Telescope was performed with the software Ansys Zemax OpticStudio [2]. Attention was focused from the early phase of the optical design in having a system that results robust to manufacturing, alignment, integration and testing (MAIT) tolerances. Many techniques are known and described in the literature to desensitize an optical design, see for example [3] and [4]. An efficient technique to achieve design robustness consists in relaying on fundamental imaging conditions - as the Abbe condition for the pupils and the Helmholtz-Lagrange invariant - and in selecting simple layouts with the strictly necessary number of optical elements. The core layout of the OSTEELoS Telescope is indeed simple, having the main mirrors M1 and M2 that share the same optical axis. The above-mentioned fundamental imaging conditions are used during the optimization also with the aim to properly evaluate the first order properties of the telescope, to achieve design robustness and to perform some necessary sanity checks, as described in [5], [6], [7], [8] and [9]. For an exotic system like the OSTEELoS telescope, it is worth evaluating the focal length with the Gauss' law, by simulating the measurement method planned for the test campaign.

The optimization is done with the multi-configuration feature of Ansys Zemax OpticStudio, which allows simulating - with discrete sampling - the different line-of-sight directions and the two different spectral ranges, namely the thermal infrared and the visible one. The shape of the freeform mirrors M1 and M2 is described with Zernike standard polynomials, while the shape of the freeform stabilization mirror and of the freeform beam splitter is described with the XY polynomials. Figure 1 shows the OSTEELoS Telescope with the ray tracing for LoS Nadir. The rays coming from the scene are dimensioned by the aperture stop, coincident with the entrance pupil of the system and travel toward the freeform concave mirror M1. After the reflection on the primary mirror M1, the rays travel toward the freeform convex mirror M2. After the reflection on M2, the rays impinge on the freeform stabilization mirror SM and are then reflected toward the Germanium beam splitter, which separates the main thermal-infrared channel in transmission from the visible channel in reflection. The first surface of the BS provides - thanks to its freeform shape - a further correction to the geometrical aberrations.

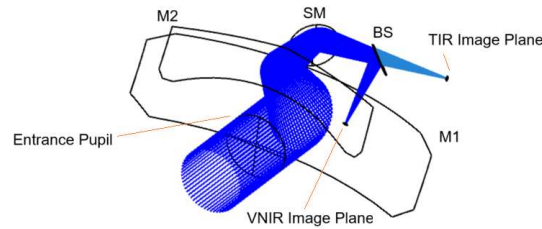


Figure 1. View of OSTEELoS. Ray tracing for Nadir LoS.

Figure 2 shows three views of the OSTEELoS telescope in the configuration of LoS + 18.5°. The left panel of Figure 2 shows the positions of the mirrors M1 and M2 when observing at line-of-sight +18.5°. In this observing configuration the optical rays use the edge portion of the optical surface of mirrors M1 and M2. The central panel of Figure 2 highlights some of the challenges of the optical design to accommodate the visible and thermal-infrared image plane in a compact cross section. Accommodating the visible image plane inside the free volume between the mirrors M1 and M2 and the thermal-infrared image plane without protruding out of the volume identified by the imaging mirrors, was a rather complex task that required some interactions during the design phase. The slight asymmetric shape of the mirrors M1 and M2 - which can be seen in the right panel of Figure 2 - contributes to succeed in this task.

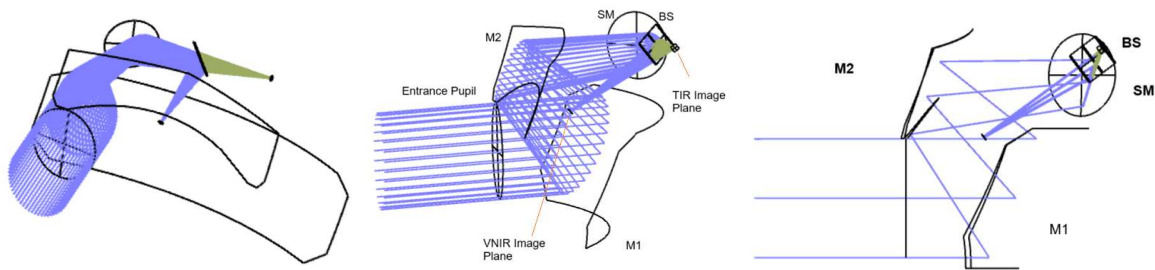


Figure 2. Left / Right: Ray tracing for LoS +18.5°.

Figure 3 shows the overlapping of three configurations, namely LoS -18.5°, 0° and +18.5°. Figure 3 makes evident the movement of the mirror M1 and M2 to observe the scene with different line-of-sight directions. The aperture-stop, the stabilization mirror SM, the beam splitter BS and the image planes do not change their position during the movement of the imaging mirrors M1 and M2 in the in-flight direction.

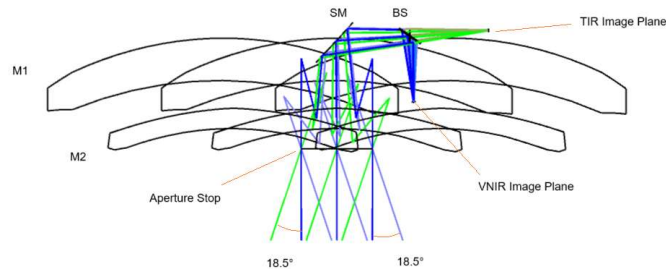


Figure 3. View of OSTEELoS for LoS 0°, +18.5° and -18.5°.

Figure 4 and Figure 5 show the quality of the nominal optical design in terms of ray aberrations and spot diagrams.

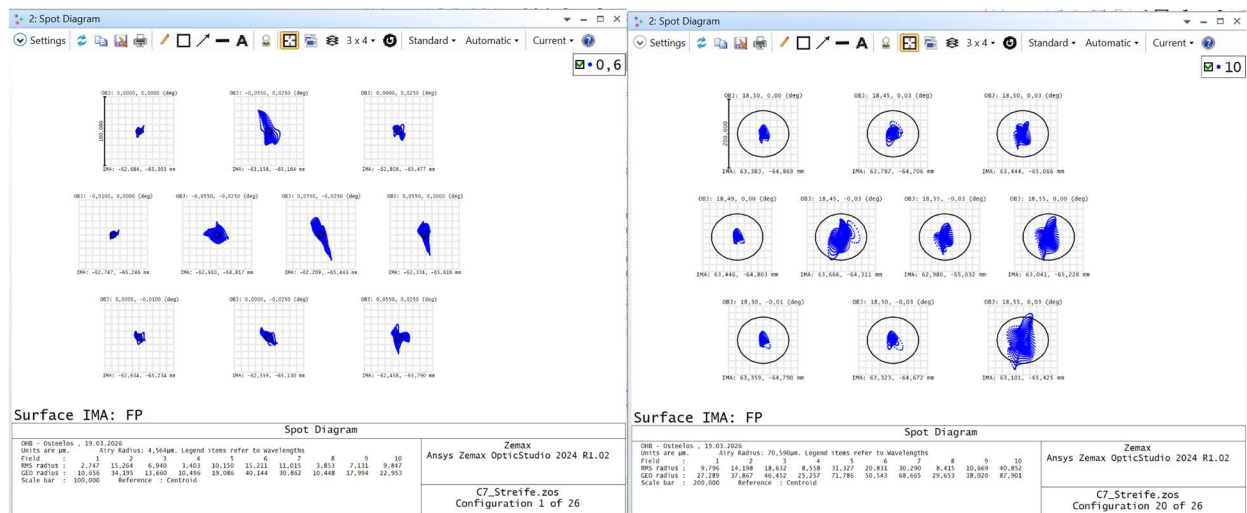
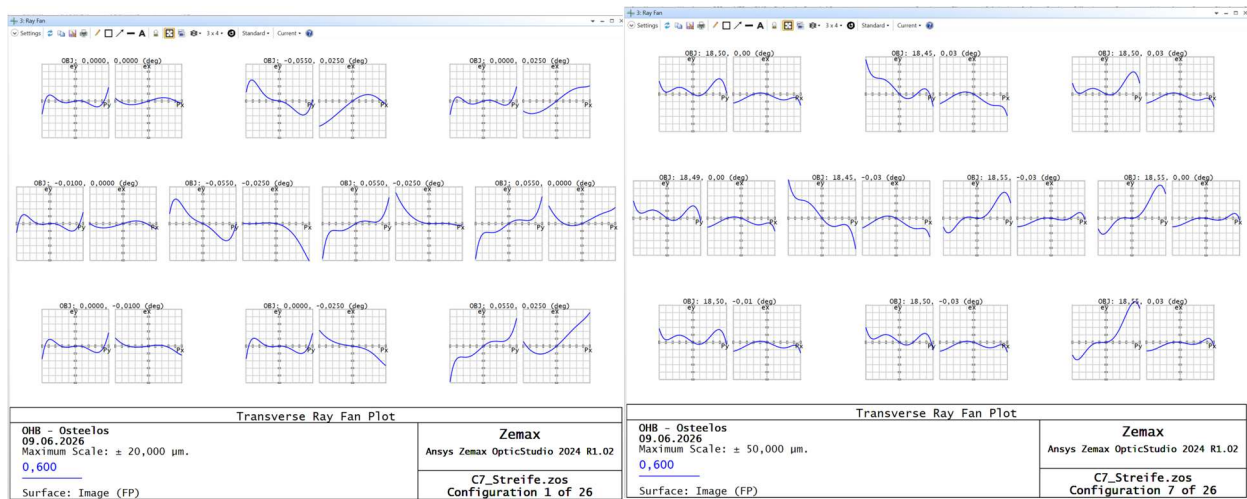


Figure 4 shows respectively in the left and right panel the ray-fan for the LoS direction 0° and 18.5° of the nominal design. For the nadir configuration, the ray fan of the nominal design is approximately 8-10 microns on axis and approximately 35-40 microns at the extreme edge of the field of view. For the LoS 18.5°, shown in the right panel of Figure 4, the ray fan is approximately 20 microns on axis and 60-70 microns at the very edge of the observed field of view. It is evident from the ray fan that the dominant uncorrected aberration is astigmatism. Coma is also present.

Figure 5 reports in the left panel the spot diagram for the configuration LoS 0° at the wavelength of 600 nm. Right panel shows the spot diagram at 10 micrometers wavelength for the configuration 18.5°. The nominal design is diffraction limited in the main channel, meaning the thermal-infrared and it shows a slightly worse image quality in the visible auxiliary channel.

For an exotic system like OSTEELoS, it is important to carefully verify the performances and the sensitivity to misalignment errors. To this extent, the total amount of uncorrected aberration - in other words the largest spot diagram - and the worst-case wavefront error RMS have been also calculated by means of the Helmholtz-Lagrange invariant, following the method described in [5]. This method interprets an aberration Δl_k as a disturbance of the invariant and evaluates the total amount of uncorrected aberrations as the difference of the Helmholtz-Lagrange invariant when passing from the object to image space divided by the image space numerical aperture $n_k \sin(u_k)$. See [5] for details. The method is easily implementable in the merit function of an optical design software, and it provides with a good approximation the residual

amount of aberration and the MTF-loss due to uncorrected aberrations. The benefit offered by this method consists in performing a sanity check of an optical design and it is especially useful for systems lacking translational and rotational symmetry and having free-form surfaces with high departures. Formulas (6) and (8) of [5] allow to evaluate respectively the total amount of residual aberration $\Delta l'_{k,design}$ and the worst-case wavefront error, obtaining 23.5 microns and 0.57 waves at 600 nm wavelength for the nadir configuration well in line with the ray-fan and the WFE evaluation obtained with Ansys Zemax OpticStudio.

The focal length of the OSTEELoS telescope does not remain constant when shifting the imaging mirrors M1 and M2 to observe the scene with different line of sight directions. Figure 6 shows the change of the focal length as a function of the line-of-sight direction. The average focal length remains approximately constant over all the LoS range.

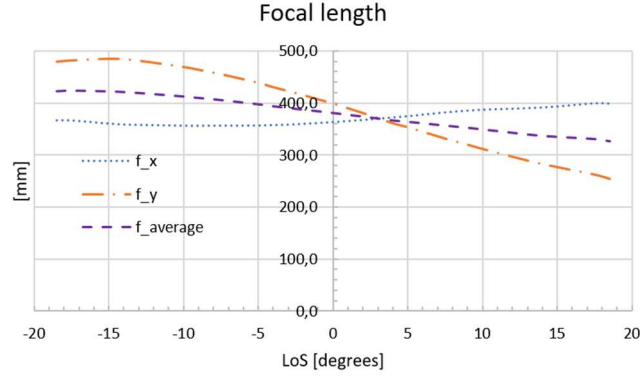


Figure 6. Focal length as a function of the LoS direction.

3. MAIT TOLERANCES

Following Table 2 to Table 4 summarize the MAIT - Manufacturing, Aligning, Integration and Testing - tolerances for the mirrors M1, M2, SM and for the beam splitter BS of the OSTEELoS breadboard. Table 2 reports the tolerances on the positioning of the mirrors along the optical axis, Table 3 reports the tolerances on the in-plane positioning, and the tolerances for the tilt X and tilt Y. Table 4 reports the surface form error (SFE) of the mirrors and BS. The SFE of mirror M1 and M2 is given pro clear aperture, or in other words for each pupil. In fact, during the movement of the mirrors M1 and M2 for the achievement of different line-of-sight directions, the optical rays impinge on different sub-pupils on M1 and M2.

The material of the mirrors M1, M2, SM is aluminum 6061 and - in the breadboard due to costs reason - also the BS is made of aluminum. In fact, it is considered sufficient to test the OSTEELoS breadboard in the visible range to validate the concept.

Table 2. Tolerances in the position of the mirrors and beam splitter.

Element	Distances along the optical axis
M1 to M2	± 0.020
M2 to SM	± 0.020
SM to BS	± 0.020

Table 3. Tolerances for the in-plane position and Tilt-X/-Y of the mirrors and beam splitter.

Optical element	In plane positions	Tilt X and Tilt Y
M1	± 0.020	± 40 arcsec
M2	± 0.020	± 40 arcsec
SM	± 0.025	± 50 arcsec
BS	± 0.025	± 50 arcsec

Table 4. SFE of the mirrors and beam splitter.

Optical element	SFE	Note	Manufacturing process
M1	40 nm RMS	On each clear aperture	Diamond turning
M2	40 nm RMS	On each clear aperture	Diamond turning
SM	20 nm RMS	On entire surface	Diamond turning
BS	20 nm RMS	On entire surface	Diamond turning

To predict the telescope performances at the end of the MAIT phase, a tolerance analysis was done with the MAIT tolerances of Sect. 3. Parabolic statistics have been applied to MAIT tolerances and, as criterium, we used the same merit function of the optimization. The used wavelength is 600 nm. The results for the expected WFE_{rms} , and for the standard Zernike coefficients Z5 and Z6, representing respectively the astigmatism at 45° and at 0° , are summarized in the following Table 5 to Table 7. At the end of the tolerance analysis the data have been processed in the LoS range $[0^\circ; \pm 15^\circ]$ as this is the travel range in which we can fully illuminate the entrance pupil of the telescope with the rotation range of the hexapod available in the optical laboratory.

Table 5. Results of the tolerance analysis for WFE_{rms} in waves.

WFE_{rms} [wv]	LoS 0°	LoS 5°	LoS 10°	LoS 15°	LoS -5°	LoS -10°	LoS -15°
min	0,063	0,078	0,178	0,211	0,078	0,200	0,182
max	1,438	1,169	1,443	1,897	1,520	1,521	1,732
average	0,444	0,463	0,553	0,713	0,475	0,568	0,683
St. Dev.	0,223	0,202	0,210	0,295	0,233	0,229	0,280

Table 6. Results of the tolerance analysis for the standard Zernike coefficient Z5 in waves.

Z5 [wv]	LoS 0°	LoS 5°	LoS 10°	LoS 15°	LoS -5°	LoS -10°	LoS -15°
min	-1,266	-1,073	-1,307	-1,797	-1,209	-1,281	-1,533
max	1,386	1,104	1,317	1,298	1,451	1,384	1,377
average	-0,029	-0,072	-0,120	-0,172	0,054	0,070	0,044
St. Dev.	0,409	0,381	0,395	0,499	0,421	0,439	0,529

Table 7. Results of the tolerance analysis for the standard Zernike coefficient Z6 in waves.

Z6 [wv]	LoS 0°	LoS 5°	LoS 10°	LoS 15°	LoS -5°	LoS -10°	LoS -15°
min	-0,689	-0,882	-1,031	-1,284	-0,805	-0,836	-1,082
max	0,842	0,782	1,041	1,062	0,793	0,702	0,892
average	0,011	-0,013	0,011	0,041	-0,048	-0,033	-0,007
St. Dev.	0,251	0,273	0,308	0,393	0,248	0,268	0,343

Left panel of Figure 9 shows the predicted WFE_{rms} as a function of the LoS in the range $[0^\circ; \pm 15^\circ]$. The lower curve is the average WFE_{rms} , the middle curve is the average WFE_{rms} plus 1 sigma level of confidence and the upper curve is the average WFE_{rms} plus 2 sigma level of confidence. Right panel of Figure 9 shows the expected behavior of the Zernike standard coefficients Z5 and Z6 as a function of the LoS in the range $[0^\circ; \pm 15^\circ]$.

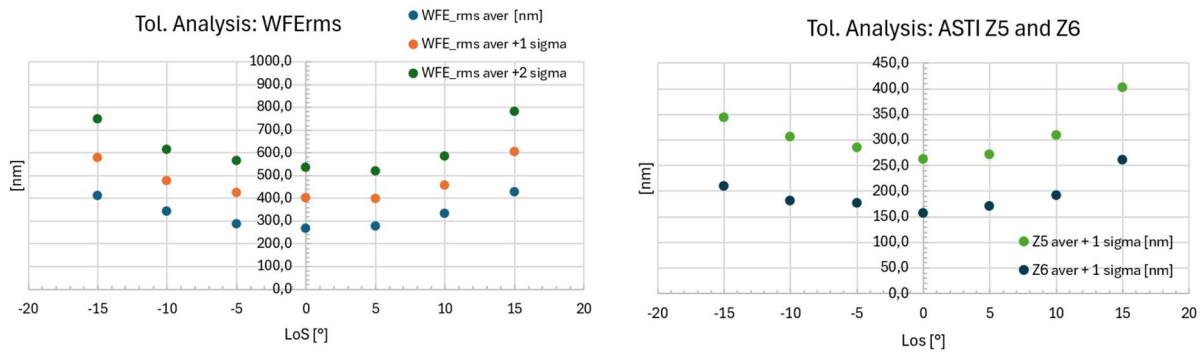


Figure 9. Result of the tolerance analysis. Left: WFE_{rms} as a function of the LoS. Right: standard Zernike coefficients Z5 and Z6 as a function of the LoS.

5.2 Application of the Nodal Aberration Theory – linear astigmatism and linear coma

This section shows an application of the Nodal Aberration Theory (NAT) on a Monte Carlo trial, the MC_T0053, randomly selected in the ensemble of 1000 files generated in the tolerance analysis. This analysis has been prepared specifically for the ICSO Conference, when the activity on OSTEELLOS was already concluded.

The NAT - see for example [1], [10], [11], [12], [13], [14], [15], [16], [17] and [18] - is a powerful tool to get a deep understanding of off-axis and misaligned systems, especially when freeform surfaces are used, see for example [17], [19], [20] and [21]. One useful tool of the NAT is the full field display (FFD), which plots the magnitude and orientation of Zernike coefficients / aberrations over a grid of points through the field of view to provide a visual aid to observe the nodal behaviour when the symmetry is broken.

To numerically calculate the positions of the nodes for the Zernike standard coefficients, the formulas of [1] can be used, nevertheless terms as quadratic constant astigmatism, linear astigmatism, linear coma and constant coma and constant astigmatism are needed and often these terms are not available in ray-tracing software. To overcome this limitation, a method based on a geometric interpretation of the field dependence of the aberrations was developed at OHB. This method allows evaluating the node(s) of any Zernike term with linear, quadratic, cubic or higher order dependence on the field, see [22].

The primary astigmatism and primary coma of the OSTEELoS telescope have a linear dependence on the field. The positions of the nodes H_n for the Zernike standard coefficients Z_5 and Z_6 in the field of view H are evaluated with the formula $H_n/H_{max} = -CA/LA$, being CA the constant linear astigmatism and LA the total linear astigmatism. A similar equation, namely $H_n/H_{max} = -CC/LC$, being CC the constant linear coma and LC the total linear coma, allows finding the nodes of the linear coma. The quantity H_{max} is the maximum field of view. The coefficients Z_5 and Z_6 represent the astigmatism respectively at 45° and 0° ; Z_7 and Z_8 represent the coma respectively in vertical and horizontal directions. Left panel of Figure 10 shows with dots the nominal rectangular field of view of the OSTEELoS telescope of $\pm 0.055^\circ$ in ALT direction and $\pm 0.025^\circ$ in ACT direction, with squares the nodes of Z_5 and with triangles the nodes of Z_6 evaluated for the Monte Carlo Trail MC_T0053 at nadir configuration with the method described above. X and Y directions are respectively the ALT and ACT directions. The node for the primary astigmatism $= \sqrt{Z_5^2 + Z_6^2}$ is in $(0.0684^\circ; 0.0801^\circ)$ for the MC_T0053 and it is placed outside the OSTEELoS FoV. Right panel of Figure 10 shows the full-field display of Ansys Zemax OpticStudio for the primary astigmatism. The FFD confirms that there is no node for the astigmatism inside the FoV in the monte Carlo trail MC_T0053.

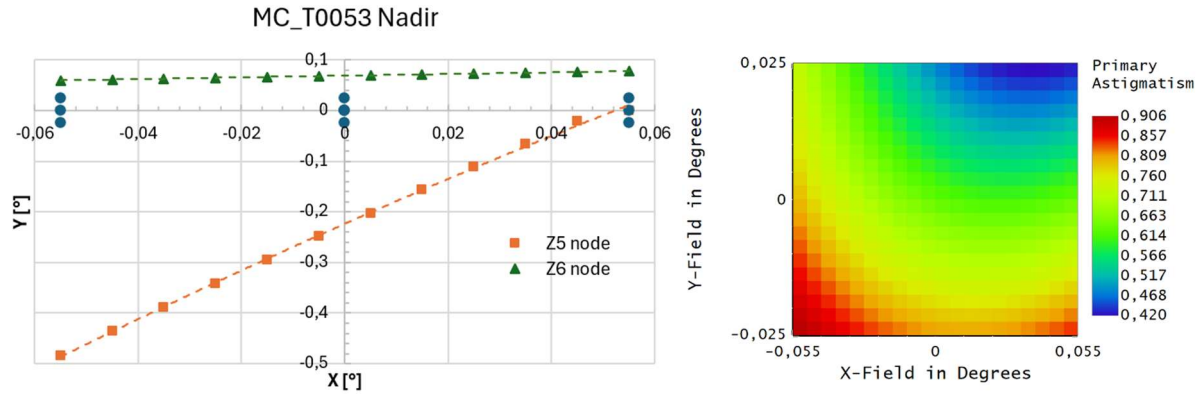


Figure 10. Left: Nodes of the Zernike standard coefficient Z_5 (squares) and Z_6 (triangles) for the Monte Carlo Trail MC_T0053. The node of the primary astigmatism is in $(0.0684^\circ; 0.0801^\circ)$. Right: FFD of Ansys Zemax OpticStudio.

We now do the same calculation for the primary coma on the monte Carlo trail MC_T0053. The left panel of Figure 11 shows with dots the nominal rectangular field of view of the OSTEELoS telescope, with squares the nodes of Z_7 and with triangles the nodes of Z_8 evaluated for the Monte Carlo Trail MC_T0053 at nadir configuration. The primary coma $= \sqrt{Z_7^2 + Z_8^2}$ has a node in $(0.0992^\circ; -0.5570^\circ)$ for the MC_T0053, placed outside the FoV. The right panel of Figure 11 shows the full-field display of Ansys Zemax OpticStudio for the primary coma. The FFD in the right panel of Figure 11 confirms that there is no node for the primary coma inside the FoV for the monte Carlo trail MC_T0053.

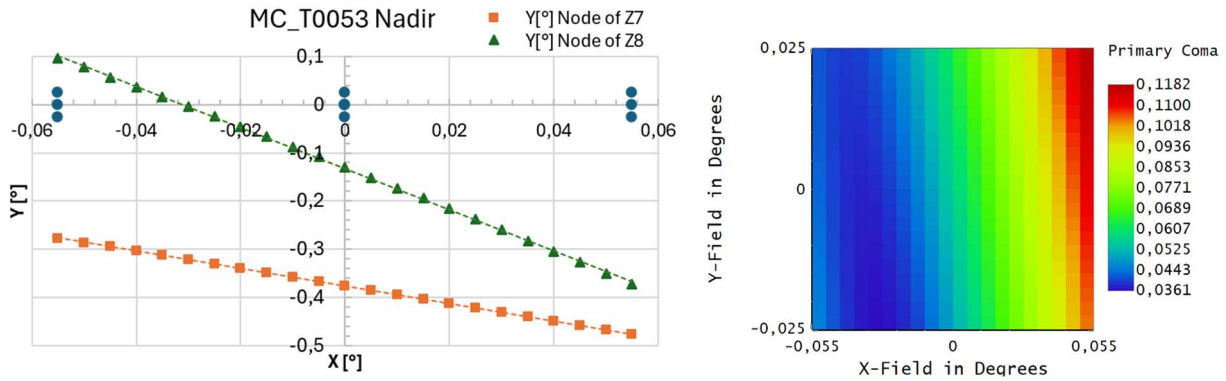


Figure 11. Left: Nodes of the Zernike standard coefficient Z_7 (squares) and Z_8 (triangles) for the Monte Carlo Trail MC_T0053. The node of the primary coma is in $(0.0992^\circ; -0.5570^\circ)$. Right: FFD of Ansys Zemax OpticStudio.

Figure 10 and Figure 11 showed the minimum of the primary astigmatism and primary coma in a misaligned system. Figure 12 shows the full-field-display of the secondary astigmatism for the Monte Carlo Trial MC_T0053.

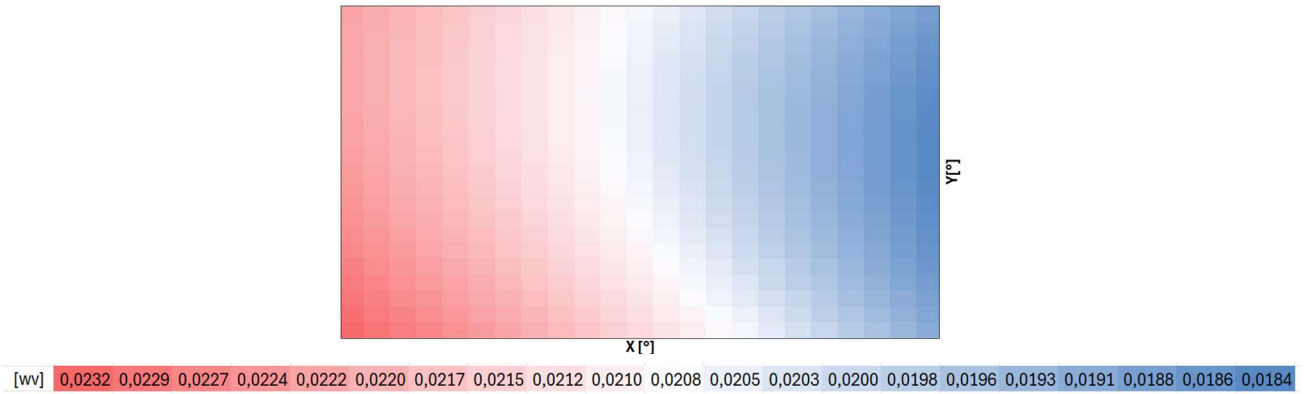


Figure 12. FFD of the secondary astigmatism for the Monte Carlo Trail MC_T0053.

To understand the effect of the MAIT tolerances it is instructive to calculate the positions of the nodes of the nominal design. Figure 13 and Figure 14 show respectively the nodes for the Zernike standard coefficients Z5 / Z6 and Z7 / Z8 and the FFD of Ansys Zemax Optic Studio of the nominal design.

In the nominal design, the primary astigmatism has one node in $(0.004^\circ; 0.018^\circ)$ and primary coma has one node in $(-0.0002^\circ; -0.00405^\circ)$. The slightly decentered position of the node of the primary astigmatism and of the primary coma in the nominal design reveals the exotic character of the OSTEELLOS telescope.

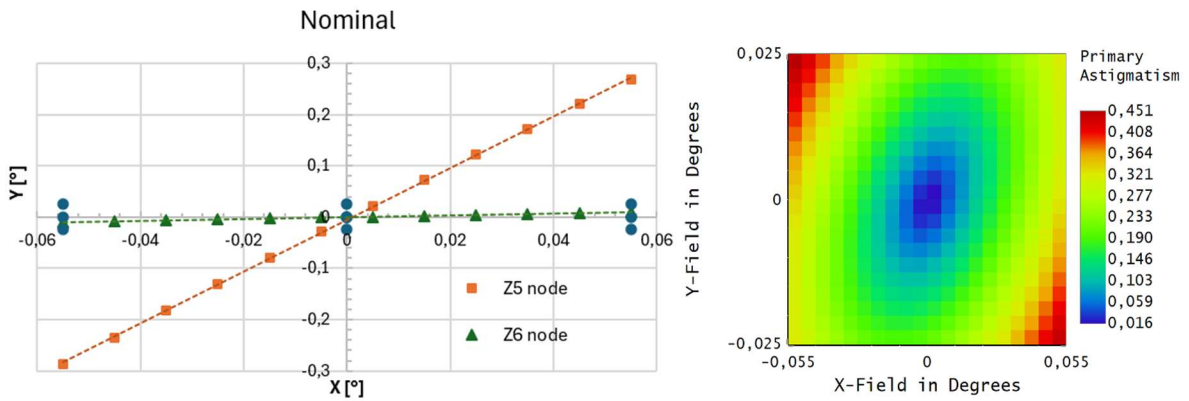


Figure 13. Left: Nodes of the Zernike standard coefficient Z5 (squares) and Z6 (triangles) for the nominal design. The node of the primary astigmatism is in $(0.004^\circ; 0.018^\circ)$. Right: FFD of Ansys Zemax OpticStudio.

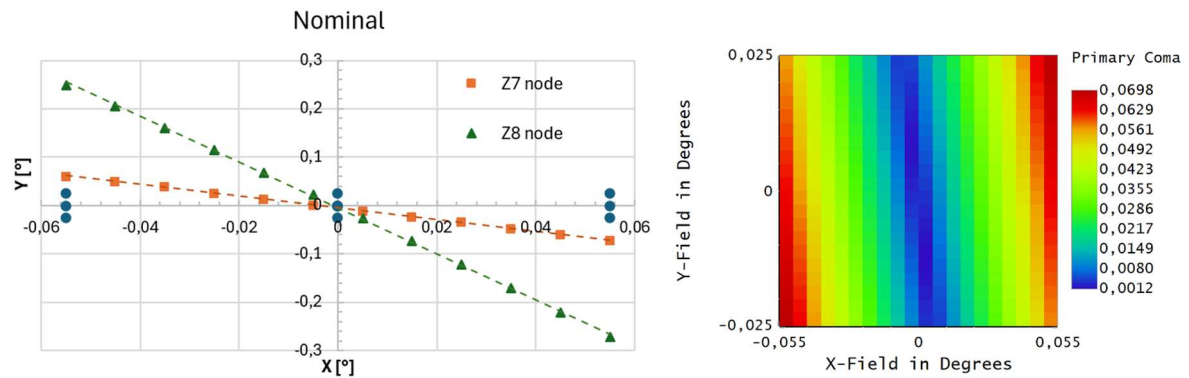


Figure 14. Left: Nodes of the Zernike standard coefficient Z7 (squares) and Z8 (triangles) for the nominal design. The node of the primary coma is in $(-0.0002^\circ; -0.00405^\circ)$. Right: FFD of Ansys Zemax OpticStudio.

The effect of the MAIT tolerances is to move away from the center the node of the primary astigmatism and primary coma. Figure 15 shows the sensitivity of the nodes of Zernike standard coefficients Z5 and Z6 to translations and rotations of M1 and M2. Values in the table give the shift in the FoV of the position of the node pro micrometer and pro arcsec.

	M1						M2					
	Tx	Ty	Tz	Rx	Ry	Rz	Tx	Ty	Tz	Rx	Ry	Rz
	[FoV°/μm]	[FoV°/μm]	[FoV°/μm]	[FoV°/arcsec]	[FoV°/arcsec]	[FoV°/arcsec]	[FoV°/μm]	[FoV°/μm]	[FoV°/μm]	[FoV°/arcsec]	[FoV°/arcsec]	[FoV°/arcsec]
node of Z5	-0,00489	-0,00058	0,00041	-0,00058	0,00179	0,00114	0,00629	0,00059	-0,00041	0,00026	-0,00002	0,00075
node of Z6	0,00006	0,00022	-0,00002	0,00009	-0,00006	-0,00010	-0,00003	-0,00006	-0,00015	-0,00037	0,00000	0,00008

Figure 15. Sensitivity of the nodes of Z5 and Z6 to translations and rotations of M1 and M2.

The analysis shown in this section remarks not only the importance of the NAT for a deep understanding of off-axis and mis-aligned optical system, but also its role in the fine alignment of an optical system. We also highlight that the NAT reveals the ultimate nature of the exotic optical design of the OSTEELoS telescope.

6. MIRRORS OF THE OSTEELoS BREADBOARD

The mirrors and the housing of the OSTEELoS breadboard have been manufactured by the German company SPACEOPTIX and they are fully compliant to the OHB specifications for SFE and for geometrical properties, such as radius of curvature, central thickness, centering of the optical axis, overall dimensions, positions and angular orientations of alignment reference surfaces. Due to cost reasons, the mirrors were manufactured with only diamond turning process. A light-weighting of the mirrors was done. Figure 16 shows the mirrors of the OSTEELoS breadboard before leaving the facility of the manufacturing company SPACEOPTIX. Figure 17 shows the measured surface form error of the mirror M1 and M2 after the subtraction of the defocus for mirror M1 and M2, respectively in the left and in the right panel. The labels S1 to S5 identify to useful clear aperture from left to right edge on the mirror, with S3 the clear aperture in the mirror center. Figure 18 shows the measured SFE of the stabilization mirror SM, of the beam splitter BS and of the back cavity mirror, after the subtraction of the defocus, respectively in the left, in the central and in the right panel. The surface form error measurements at component level and the micro-roughness measurements have been performed by the manufacturing company SPACEOPTIX. All the optical elements present a micro-roughness value between 2 and 5 nm rms.

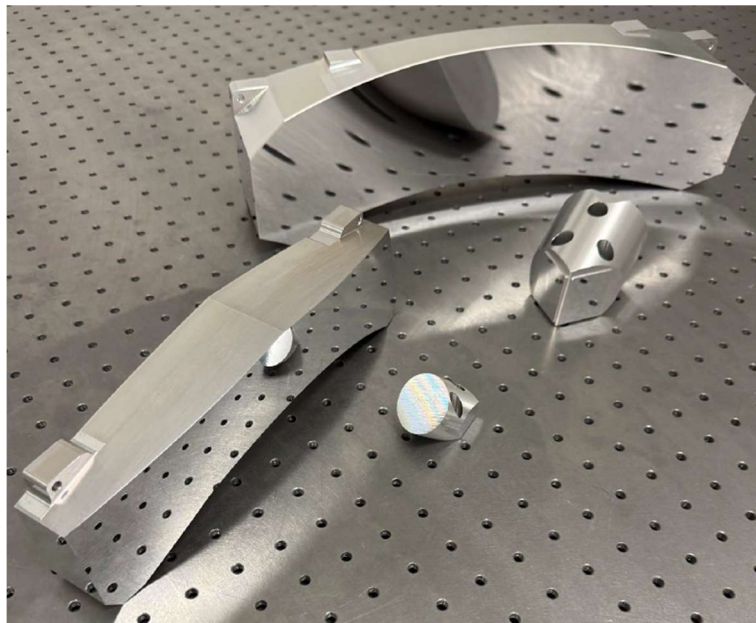


Figure 16. Mirrors of the OSTEELoS breadboard at the facility of the manufacturer SPACEOPTIX.

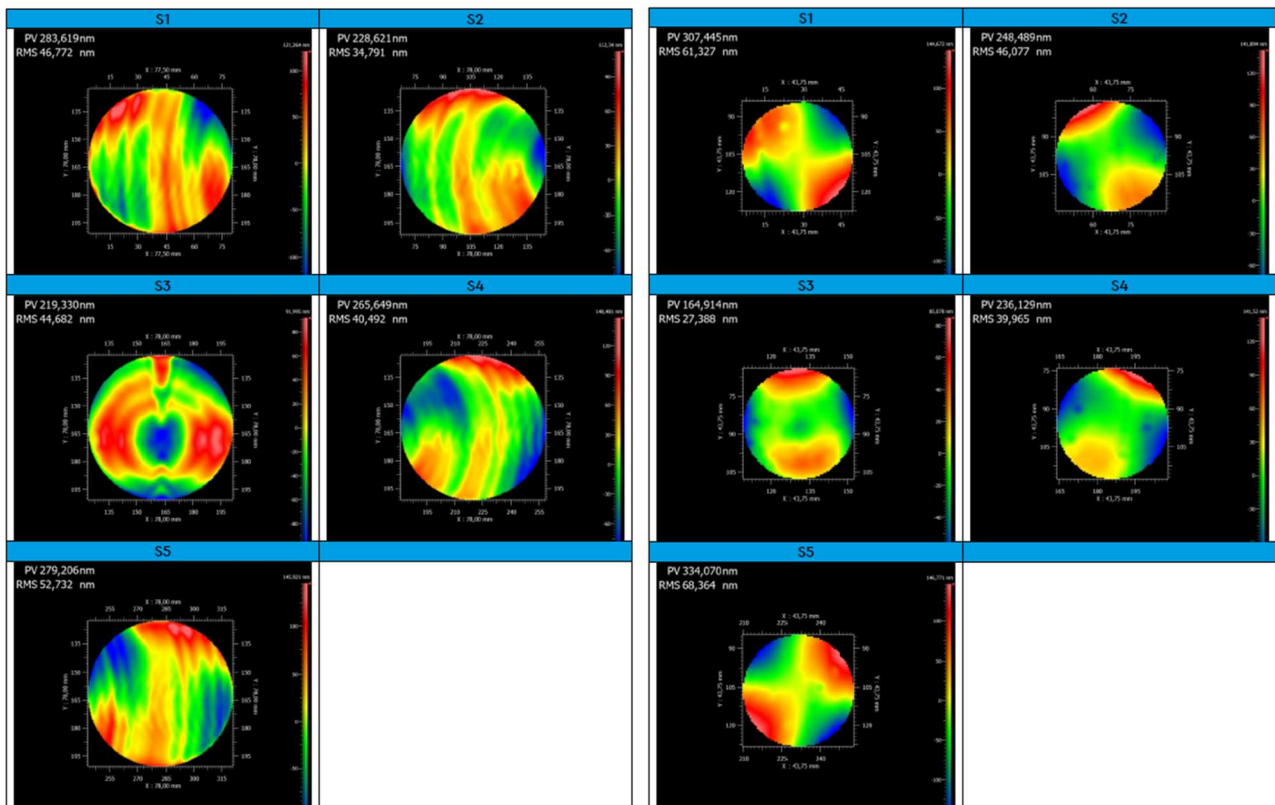


Figure 17. Left / Right: measured SFE of M1 / M2 per sub-pupil with defocus subtracted. Courtesy of SPACEOPTIX.

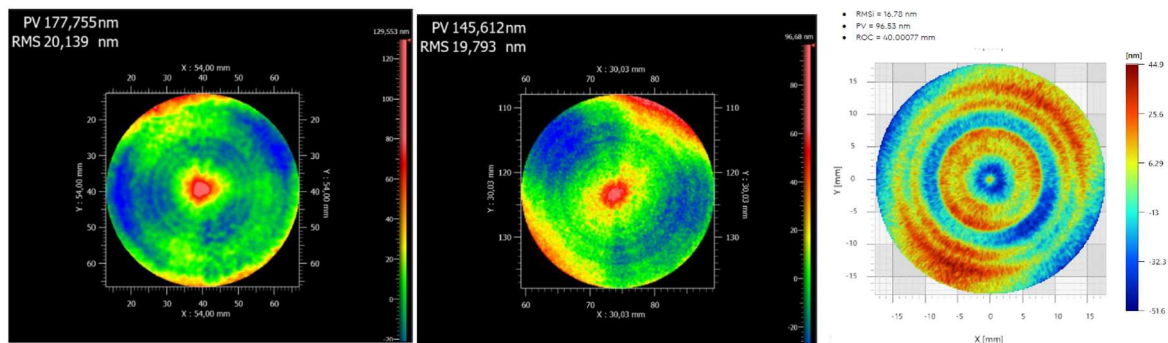


Figure 18. Left / Center / Right: measured SFE of SM / BS / back cavity mirror with defocus subtracted. Courtesy of SPACEOPTIX.

7. INTEGRATION AND ALIGNMENT OF THE OSTEELOS BREADBOARD

The integration and alignment of the 4 free-form mirrors have been performed at OHB premises in an ISO8 optical laboratory. The alignment strategy has been based on interferometric and geometrical measurements relying on alignment reference surfaces. No CMM-aided measurements have been performed.

Mirrors M1 and M2 are mounted on 5-axis adjustment stages allowing finding the desired relative position and orientation. The integration and alignment phases were performed in few days. Integration and alignment were considered successfully when the tolerances of Sect. 3 were achieved.

Figure 19 shows the mirrors and some of the mechanical components during the incoming inspection at OHB premises in the ISO8 optical laboratory. The back cavity mirror - specifically designed and manufactured to allow the testing of the OSTEELOS breadboard - can also be seen on the top right of Figure 19.

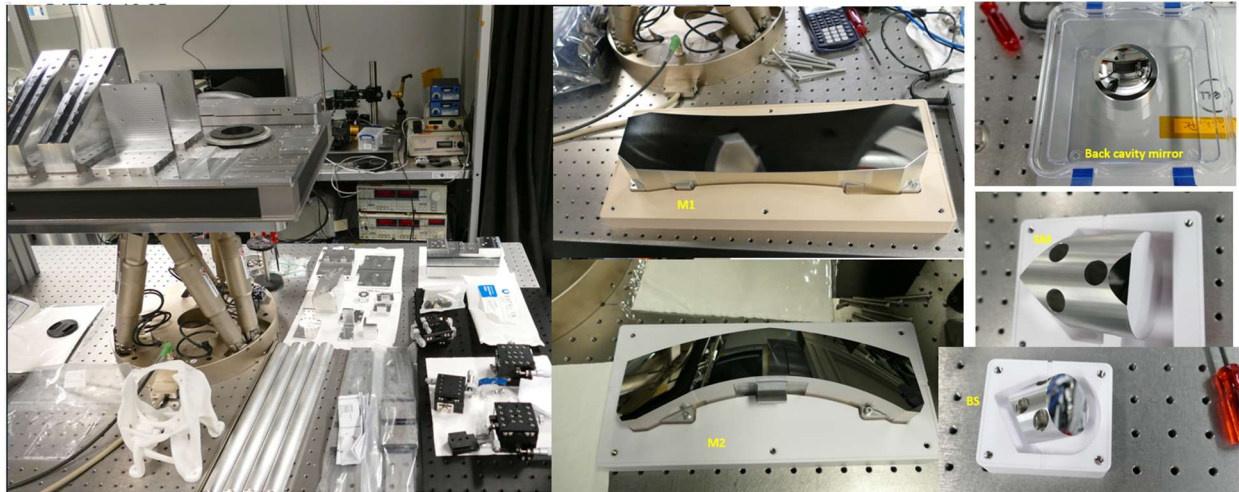


Figure 19. Incoming inspection at OHB of the opto-mechanical parts before the integration.

Figure 20 shows the integration phase of the mirror M1 on its 5-axis alignment stage. The beam splitter, the stabilization mirror and the back side of the side of the light-weighted M1 can also be seen.

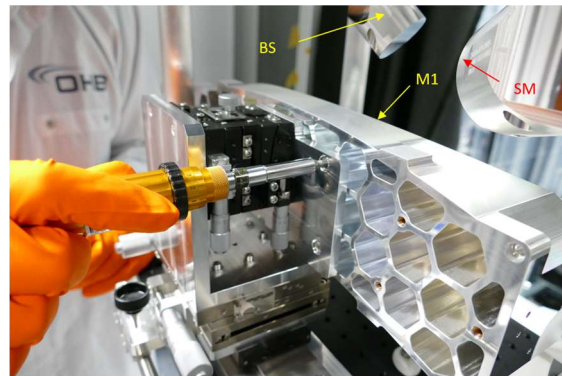


Figure 20. Mounting the mirror M1 on its 5-axis adjustment stage.

8. OPTICAL MEASUREMENTS: WFE, FOCAL LENGTH, DISTORTION AND MTF

This section describes the results of the optical characterization of the OSTEELOS breadboard performed in the ISO8 optical laboratory of the OHB premises in Oberpfaffenhofen. The wavefront error and the focal length were measured in the line-of-sight range of $\pm 15^\circ$. The MTF at the wavelength of 10 microns was derived from measurements and analysis.

8.1 WFE measurements

The WFE measurements of the OSTEELOS telescope have been performed with a Zygo 6" aperture interferometer installed on an anti-vibration optical bench, working at the wavelength of 632.8 nm.

Figure 21 shows in the left and right panels the telescope in the set-up for the WFE measurements at LoS 0° and $+15^\circ$ respectively. The OSTEELOS breadboard is accommodated on a small optical bench mounted on a hexapod. A mechanical support with triangular cross-sectional shape tilted of approximately 30 degrees with respect to the horizon allows having the optical axis of OSTEELOS parallel to the optical axis of the interferometer. The left panel of Figure 21 shows with labels the main optical elements, the interferometer and the optical axis. It is interesting to observe how close M1 and M2 are or in other words the compact cross section in the in-flight direction, which is perpendicular to the page. The OSTEELOS breadboard has a volume of $600 \times 475 \times 345 \text{ mm}^3$. No big effort was adopted in the breadboard to limit the mechanical volume and the cross section of 345 mm, as the main purpose is to validate the concept of moving the mirrors along the ALT direction to change the LoS direction.

The WFE of the OSTEELoS telescope is measured in double pass in an interferometric cavity realized by means of a transmission flat (TF) installed on the interferometer and a spherical concave back cavity mirror with 16 nm RMSi surface quality, specifically manufactured for testing the OSTEELoS breadboard. The spherical concave back cavity mirror is installed on the breadboard, as shown in the right panel of Figure 21.

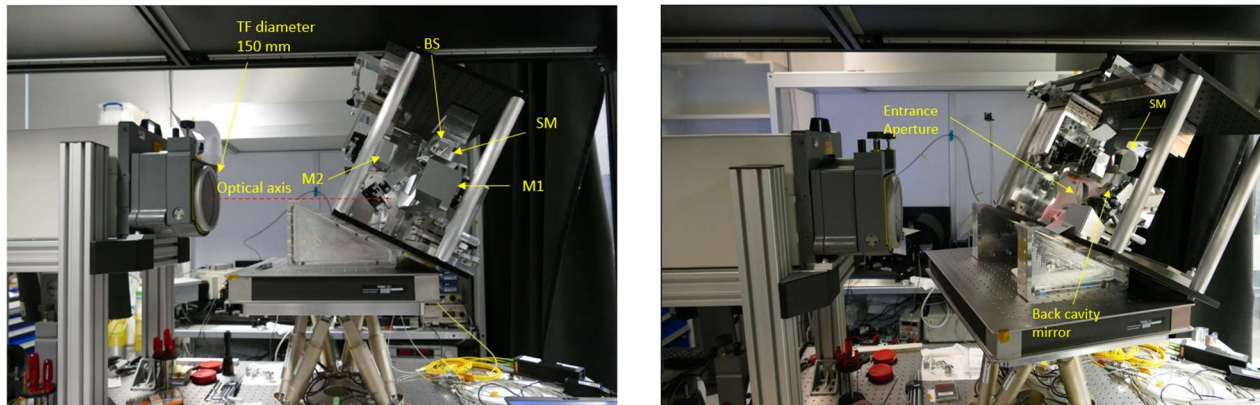


Figure 21. Left / Right: Set-up for WFE measurement of the OSTEELoS telescope at LoS 0° and 15°.



Figure 22. Left: Frontal view of the OSTEELoS breadboard during the WFE measurements at LoS 0°. Right: Back view with atto-cubes for mirrors M1 and M2.

Left panel of Figure 22 shows a frontal view of the OSTEELoS breadboard during the WFE measurement for the nadir configuration. The figure conceptually shows the optical axis of the interferometer, the aperture stop – coincident with the entrance pupil of the telescope, the mirror M1, the back side of the mirror M2 and the beam splitter. The WFE has been measured starting from the configuration LoS 0°, meaning that the optical axis of the OSTEELoS breadboard and of the interferometer are parallel. The mutual alignment between interferometer and OSTEELoS breadboard is performed by means of a reference surface, machined on the back side of the mirror M2 on which a plano-parallel plate can be temporary accommodated during the alignment phase.

For this initial configuration an adjustment of the position and orientation of the back cavity mirror is necessary. After having performed the WFE measurement for the LoS 0°, the mirrors M1 and M2 are manually moved to the nominal positions for the LoS +5°, +10°, +15°, -5°, -10° and -15°. The mirrors were placed in the nominal position of the optical design. Atto-cubes installed on the breadboard allowed the positioning of the mirrors M1 and M2 with micrometric precision, see right panel of Figure 22. The hexapod was tilted for each LoS orientation to simulate the LoS direction under test. As a note we report that during the movement of the mirrors M1 and M2, necessary to realize different LoS positions, the focus position of the back-cavity mirror was not adjusted. Its position was adjusted only during the first measurement.

Figure 23 summarizes the results of the WFE measurements and compares the WFE measurements in the LoS range $\pm 15^\circ$ to the WFE requirement. The measured WFE of the OSTEELoS breadboard is compliant to the requirement of WFE. Furthermore, we observe that the measured dependence of the WFE on the LoS is in agreement with the results of the tolerance analysis, see left panel of Figure 9.

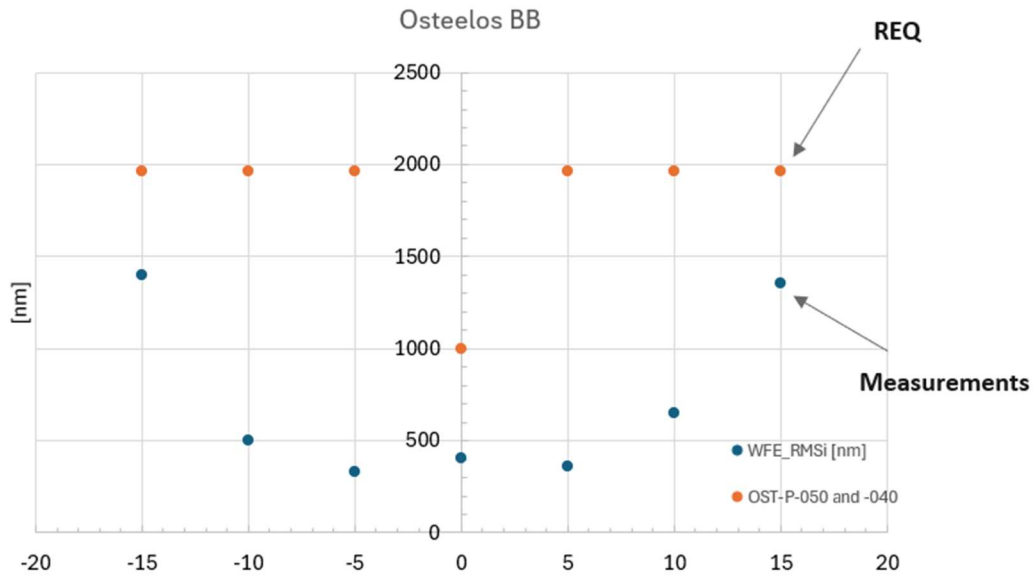


Figure 23. Results of the WFE rms measurements of the OSTEELoS breadboard.

Figure 24 shows in the top line the measured WFE map and in the bottom line the measured interferogram, for different line-of-sight positions from -15° in the left panel to $+15^\circ$ in the right panel. The entrance aperture of the OSTEELoS breadboard of 78 mm is always fully illuminated. The dominant aberration is clearly the astigmatism.

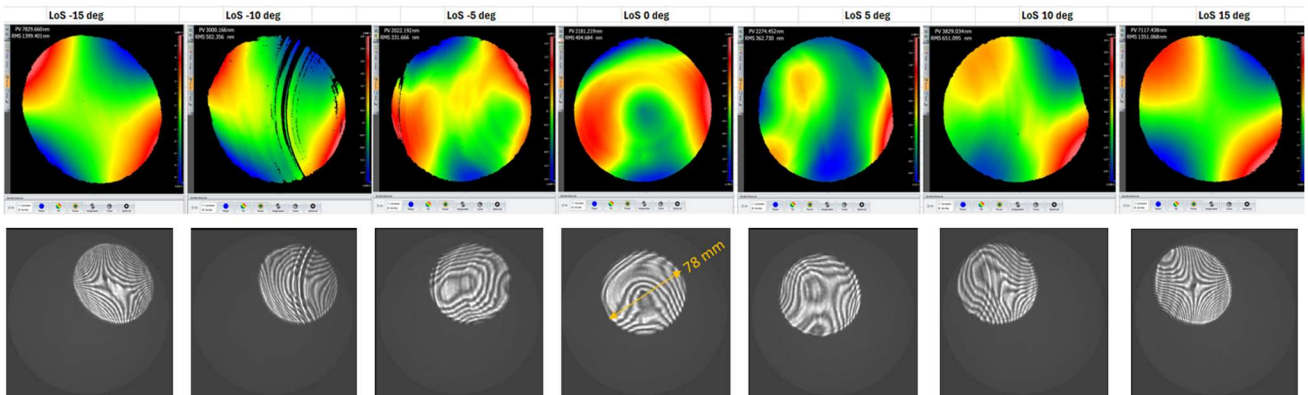


Figure 24. Measured WFE maps (top) and interferograms (bottom) of the OSTEELoS breadboard for different LoS positions.

From the measured WFE we evaluated the MTF in the infrared at the wavelength of 10 micrometres. To this aim the measured WFE is imported in Zemax OpticStudio after having converted it from .INT into .DAT. Then a scaling between the wavelength of the interferometer of 632.8 nm and the desired wavelength of 10 μm is applied. Afterwards, the MTF is evaluated by means of a paraxial lens having the same relative aperture of the OSTEELoS telescope. The results are shown in bottom line of Figure 25 and they show that the optical quality of the OSTEELoS breadboard is almost diffraction limited at 10 microns wavelength in the line-of-sight range $\pm 10^\circ$. A degradation in the MTF is evident for the LoS orientations $+15^\circ$ and -15° .

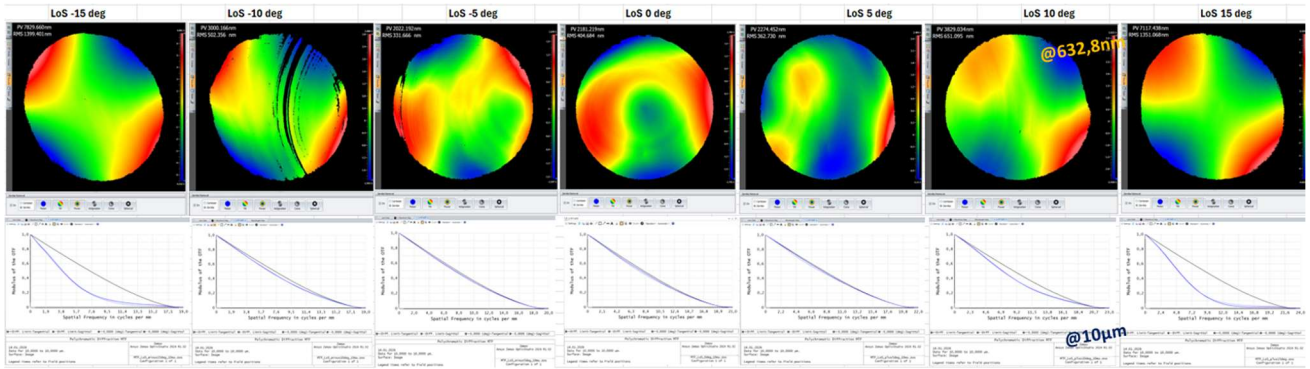


Figure 25. Measured WFE at 632.8 nm (top) and estimated MTF at 10 μm wavelength (bottom) of the OSTEELoS breadboard for different LoS positions.

Note: Some discontinuities are evident in some of the measured WFE maps, e.g. when the rays impinge on the lateral side of M1 and M2 for the configuration LoS -10°. The reason for these discontinuities is that the mirrors – due to costs reasons – have been manufactured and polished only with diamond turning.

8.2 Focal length measurement

The focal length of the OSTEELoS breadboard has been measured by means of a Möller-Wedel autocollimator with 500 mm focal length and 52 mm clear aperture and of an auxiliary camera model IDS1490 SE-M with resolution 3840 H x 2748 V and with pixel size 1.67 μm . The back-cavity mirror used for the WFE measured is now substituted with the auxiliary camera. The camera is mounted on a 5 axes adjustable stage, see Figure 26.



Figure 26. Alignment of the auxiliary camera with the autocollimator 5/140.

The first step consists in aligning the auxiliary camera, so that its sensitive area coincides with the image plane of the telescope. To achieve this, a Möller-Wedel autocollimator 5/140 with focal length 140 mm and aperture 28 mm is used, as it presents a fan of selectable targets. The autocollimator is mounted on a dedicated support, in front of the optical bench holding the telescope, see Figure 26. The position of the autocollimator is kept fixed, whereas the position of the telescope is adjusted in horizontal and vertical position, and in angular orientations through the hexapod.

After a good angular relative alignment between autocollimator and OSTEELoS telescope is achieved, the position of the telescope is moved to have the beam of the collimator illuminating the centre of the telescope aperture. To align the auxiliary camera, we selected the USAF 1951A target in the Möller-Wedel Autocollimator 5/140.

Figure 27 reports some acquired pictures during the alignment of the camera. Once the auxiliary camera has been aligned, the Möller-Wedel autocollimator 5/140 is substituted with the Möller-Wedel 10/500, see Figure 28, which projects a crossline target into the telescope. The Möller-Wedel 10/500 is aligned with respect to the telescope, by using an alignment reference surface machined on the backside of mirror M2.

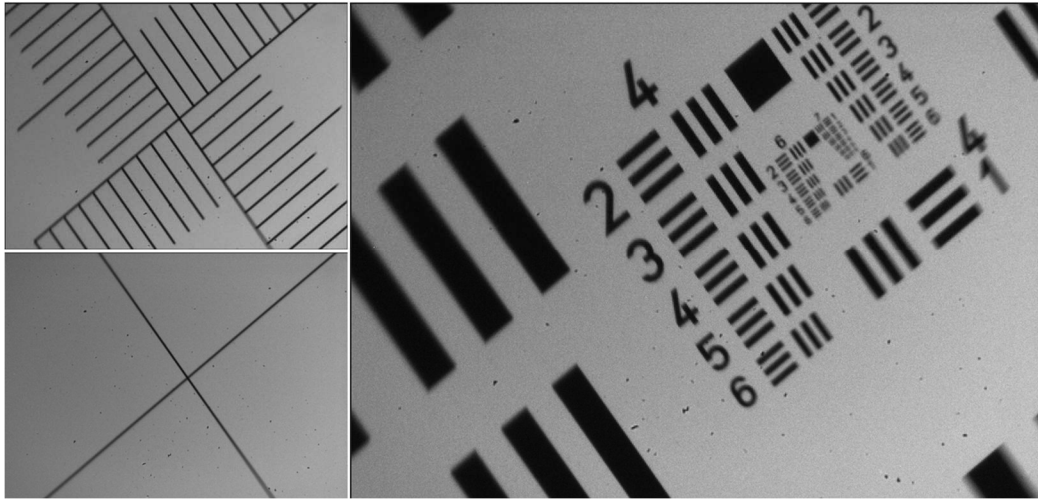


Figure 27. Acquisition of images for the alignment of the auxiliary camera of the OSTEELoS telescope.

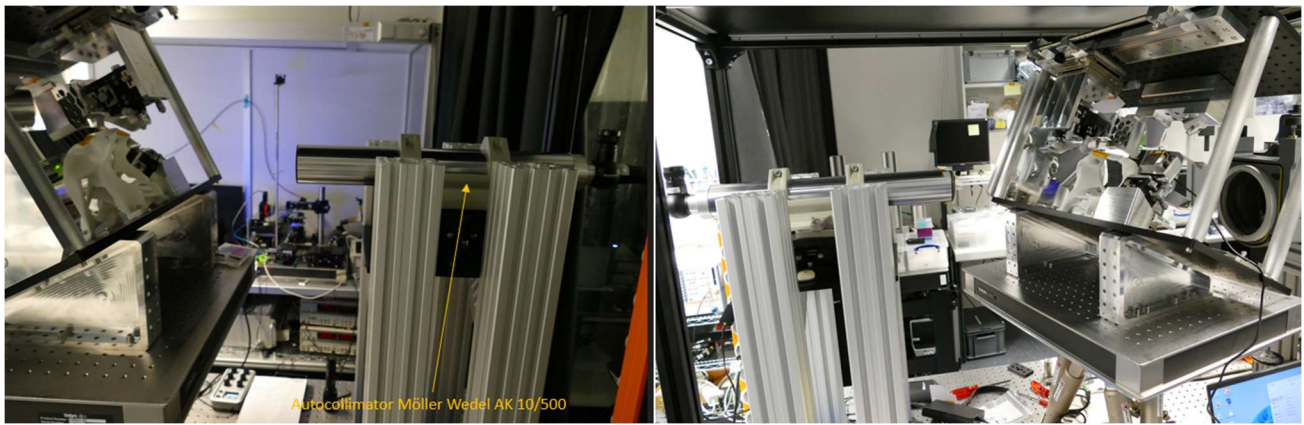


Figure 28. Focal length measurements with the autocollimator Möller Wedel 10/500.

The telescope, see Figure 28, is rotated stepwise by means of the hexapod and the position of the projected cross-reticule is recorded. The focal length is evaluated from the measured shift of the projected cross-reticule by means of the law of Gauss. The measured value of the focal length and a comparison with the expected theoretical values of the optical model of the OSTEELoS telescope is given in Table 8.

Note: In the focal length measurements, we succeeded in achieving a slightly larger LoS range, namely $[-17.5^\circ; +17.5^\circ]$.

Table 8 Measured and theoretical focal length of the OSTEELoS telescope.

LoS [°]	measured values			optical model		
	fx [mm]	fy [mm]	average [mm]	fx [mm]	fy [mm]	average [mm]
-17,5	521,1	462,7	491,9	528,8	471,4	500,1
-10	507,2	477,2	492,2	503,2	490,3	496,8
-5	486,7	478,6	482,7	492,7	491,7	492,2
0	503,7	488,5	496,1	488,0	489,1	488,6
5	470,8	488,5	479,7	487,3	479,9	483,6
10	484,1	468,2	476,2	493,3	470,1	481,7
17,5	499,4	452	475,7	508,5	449,7	479,1

Left panel of Figure 29 shows the cross reticule acquired in two angular positions. Being the detector tilted around the optical axis and not having the possibility to clock it in the breadboard, the acquired image appears rotated with respect to

the horizon. The right panel of Figure 29 shows the geometric relationship between the angular shift and the movement of the centre of the cross for the application for the Gauss' law to evaluate the focal length. Simple mathematical relationships allow the calculation of the focal length.

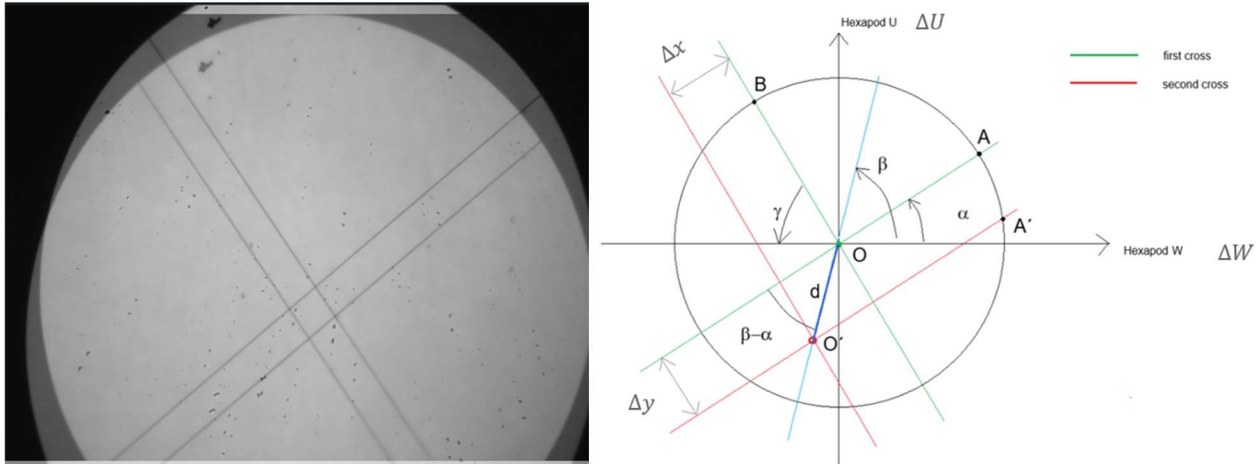


Figure 29. Left / right: acquired image of a cross reticule / geometric relationship.

8.3 Compliance table

Following Table 9 summarizes the compliance status of the breadboard of the OSTEELoS telescope for the measured WFE rms and focal length.

Table 9 Compliance status of the OSTEELoS breadboard.

Optical parameter	Requirement	Measured values	Status
WFErms	< 1000 nm axis	404 nm	Compliant
	< 1960 nm for all LoS	1399 nm (worst case LoS -15°)	
Focal length	488 +/- 10 mm (*)	496.1 mm	Compliant

9. CONCLUSIONS

The work presented in this paper demonstrates the feasibility of a telescope with a scanning mechanism to perform persistent videos. The design has an intrinsically small cross section in the flight direction that reduces the atmospheric drag, this makes this design suitable for operations on a VLEO platform.

The paper reports the results of the test campaign on the breadboard of the OSTEELoS freeform telescope, which was designed, integrated, aligned and optically tested by OHB Germany in the Oberpfaffenhofen premises. The wavefront error and the focal length of the telescope were measured. The MTF at 10 micrometers wavelength was derived by combining WFE measurement in the visible and analysis.

The successful measurement campaign performed on the OSTEELoS breadboard demonstrates the validity of the *Magócs* concept – so named after the inventors L. Maresi and T. Agócs. According to this concept it is possible to change the line-of-sight direction of an imaging telescope by shifting the main imaging mirrors. This novel aspect avoids the use of a flat scanning mirror in front of the instrument, with benefit in the reduction of the instrument cross section. The OSTEELoS Telescope is therefore a suitable candidate for flying at VLEO and making persistent videos of the Earth.

The next step is the realization and the test of an elegant breadboard of the OSTEELoS telescope, where the movement of the mirrors M1 and M2 is realized with electrical motors. The elegant breadboard is currently in the design phase with the aim to further limit the overall volume and especially the cross section in the in-flight direction. The mirrors will be the same ones of the breadboard. The testing phase is planned for the end of this year / beginning next year. It is planned to measure the WFE of the elegant breadboard. It will be also interesting to map the primary coma and primary astigmatism during the WFE measurement, by performing measurements scanning the ACT direction (Y direction). This will allow applying the NAT for the evaluation of the node (or minimum) positions of the primary astigmatism and primary coma of the aligned elegant breadboard and evaluate in this way the obtained degree of aligned.

10. INTELLECTUAL PROPERTIES RIGHTS

The paper is based on an ESA patent. The patent application was submitted in February 2025. The reference application number is [EP25157330.9](#).

11. ACKNOWLEDGEMENTS

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