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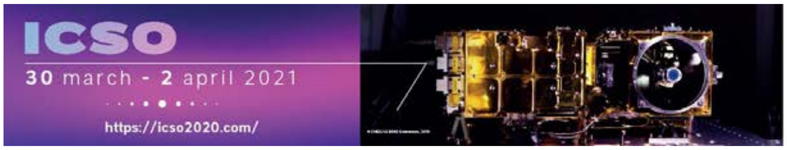

Alignment turning and assembly of the Sentinel 4 optical modules

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Alignment Turning and Assembly of the Sentinel 4 Optical Modules

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1. INTRODUCTION

Centering and positioning of the single optical elements within a lens system are essential for the quality of high precision optics. The positioning of the lenses has to be long term stable and shall withstand space environment to keep the performance of the optical system over years. This applies in particular to the optical modules for the Sentinel-4/Ultraviolet/Visible/Near-Infrared (UVN) sounder instrument /1/. In order to fulfill these requirements, an appropriate opto-mechanical design and a deterministic assembly technique based on well-defined assembly interfaces are necessary. For this reason, the application of the alignment turning technology /2/ is particularly suitable. The basic approach is to achieve the best possible coincidence between the optical axis of the lens and the mechanical axis of the lens cell and drop the lens stack in a barrel with a tight fitting. By machining the lens housing in respect to the optical axis, the resulting ultra-precise references planes significantly simplify the alignment and integration of the objective. The assembly becomes deterministic – extensive alignments are not required. The mechanical and environmental specifications are achieved by the consistent compliance with:

- ultra-precise machined mounting interfaces,
- avoiding adjustment mechanisms, and
- the application of a defined pre-load during lens mounting.

1.1 Alignment turning approach for the S4 UVN optical modules

The S4 UVN optical modules requires a resulting decenter shift of each optical surface to the best fitting optical system axis less than 4 µm for the telescope (TOA), camera (CAM), and collimator optics (COL) and less than 6 µm for the NIR spectrometer optics (NSA). The total tilt of each surface to the best fitting optical axis has to be within 6 arcsec. The individual lens position (air distances) as well as the position of the lens stack in the direction of the optical axis have to be within 5 µm, respectively. Aiming to the specified values, the alignment turning technology was carried out on the flight models (PFM, FM2) of the UVN instrument optics.

Table 1. S4 UVN optical modules and number of items to be alignment turned and assembled

S4 UVN optical modules listing

Optical Module	*items*
Telescope optics (TOA)	6 lenses, 3 rings
Collimator optics (COL)	5 lenses, 2 rings, 1 GRISM (grating-prism-assembly)
Camera optics (CAM)	5 lenses, 3 rings
NIR spectrometer optics (NSA)	3 lenses, 3 rings

1.2 Manufacturing and integration workflow

The alignment turning and assembly of all Sentinel 4 Optical Modules follows a consistent method that can be break down in a set of manufacturing and integration processes shown in figure 1. After the initial inspection of the lens tube and the lens subassemblies (lenses glued into the lens housing), all items are characterized by means of dimensional metrology (refer to 2.2). The measurement results and the as-built optical data of the objective are the basis for the calculation of the required dimensions of the lens housings. The alignment turning process (refer to 2.1) realizes the target dimensions for the lens housing diameter and vertex heights that are well centered on the optical axis of the lens in an iterative process. The multi-stage cutting-measurement-cycle ensures the compliance with the target dimensions in a precision of ≤ 2 µm. The final results of one lens assembly are given in to an as-built data analysis to calculate adjusted target values for the following lens assembly. After finishing the mechanical manufacturing by alignment turning, the lens assemblies will be cleaned and inspected prior to the joining process. The joining is a passive, so called "drop-in" assembly: the lens stack is filled in the tube without further alignment activities using a dedicated joining equipment (refer to 2.3). The exact positioning of the lenses within the tube is determined by the ultra-precise machined lens housing geometry, which benefits from tight fitting in the range of single micrometers between the tube and the lens cells. Once the lens stack is integrated into the tube, the system assembly has to be locked and preloaded to withstand shock and vibration loads. Therefore, the clamping process (detailed in 2.4) applies an exact preload onto the lens stack. Based on the knowledge of the spring characteristics and by measuring the effective assembly gap, an alignment turned end ring closes the lens assembly by applying a determined pre-load.

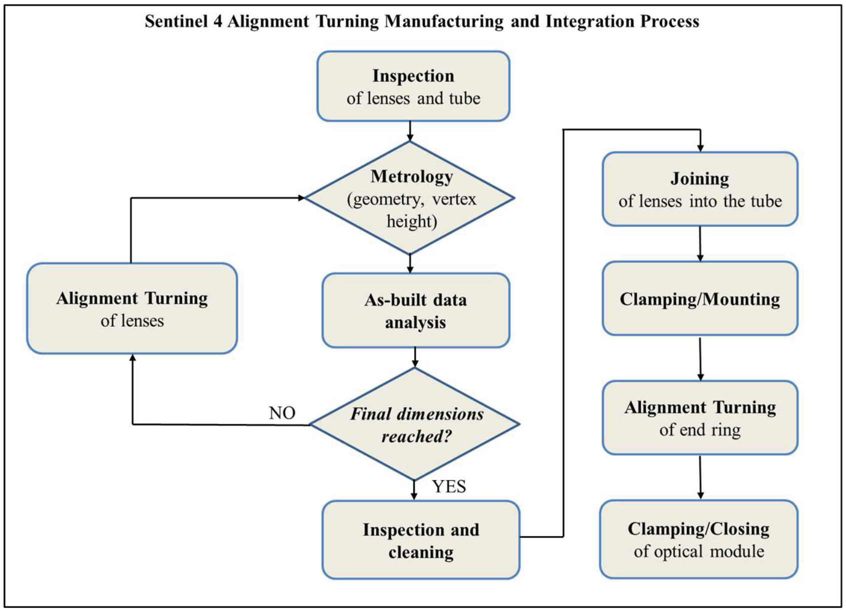


Figure 1. Scheme of the manufacturing and integration workflow.

2. INVESTIGATIONS

2.1 Alignment turning

The alignment turning technology is known as a deterministic assembly technology for high-quality optics. Typical applications are optics for inspection lenses for UV or EUV, microscopy, and high level photographic optics. The process is based on the diamond machining of the outer geometry of a lens cell (housing) in relation to the optical axis of the lens. The technology is investigated and improved over years to a reliable manufacturing process /3/, /4/. The usual procedure will be as follows: detecting the optical axis of the lens by optical metrology, alignment of the optical axis into the turning spindle axis, cutting the lens housing outer diameter as well as the top and bottom rim (figure 2).

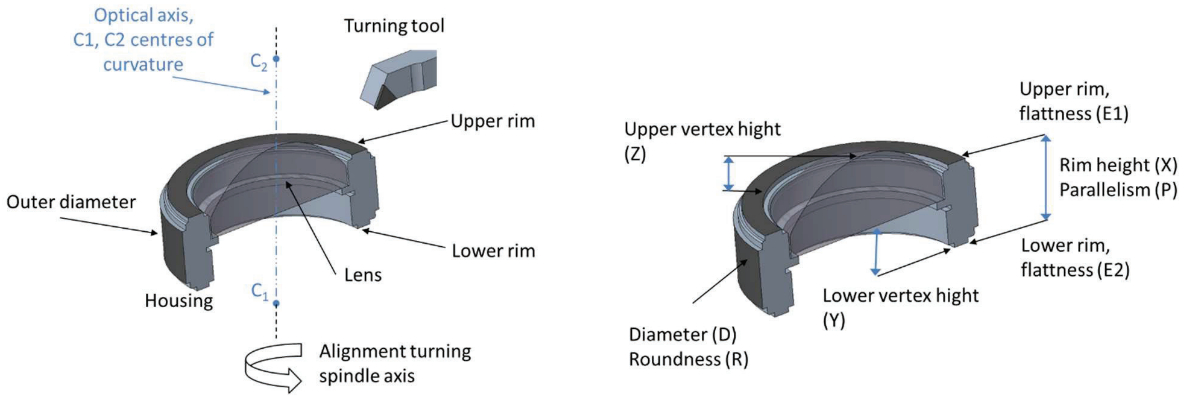


Figure 2. Alignment turning of a lens cell. Left: optical axis (OA) aligned to spindle axis and cutting the reference surfaces in respect to OA. Right: geometrical dimensions and parameters determined by the alignment turning process.

To fulfill the demands of the Sentinel 4 optical modules, the standard alignment turning process was investigated and optimized in particular with regard to:

- alignment accuracy of the optical axis into the turning spindle axis,
- azimuthal orientation of aspherical surfaces, and
- minimisation of lens cell deformations during the process.

The accuracy of the alignment turning process strongly depends on the used diamond turning spindle that incorporates the reference axis, while detecting the centers of curvature and the machining steps. In case of the Sentinel S4 optical modules, the customized alignment turning machine, developed by IOF, is equipped with a hydrostatic spindle. The remarkable stiffness of the turning spindle provides an axial and lateral runout well below 0.1 µm, even under the process-related unbalanced machining.

In order to ensure the correct referencing of the lens housing geometry, the centration of the lens is controlled after the alignment turning process. This is carried out by applying the same metrology approach that is already used for the lens alignment. The centers of curvature (C1, C2) of both lens sides are detected with a focused autocollimator /5/, while the lens assembly is still mounted on the turning spindle. By rotating the reference axis, the remaining runout of C1 and C2 is measured with the help of a calibrated CCD camera. Taking into account the lens data, the lateral shift of each lens surface, defined by the runout of the center of curvature in relation to the reference turning axis, can be determined as a quality criterion for the alignment turning process. The surface tilt error can be used to characterize the centration of the lens surfaces, respectively. Table 2 shows typical alignment turning results that are exemplary for the TOA FM2 flight model.

Table 2. Measurement results of lens surface centration on alignment turning spindle for the TOA FM2

Centering errors (run out) of the optical surfaces w.r.t. the reference axis (alignment turning axis) of the TOA FM2.

Optical element	*Runout diameter C1 [µm]*	*Runout diameter C2 [µm]*	*Surface tilt C1 [arcsec]*	*Surface tilt C2 [arcsec]*
TES 1	0.8	0.8	2.5	0.9
TES 2	1.1	0.7	2.7	1.1
TES 3	1.1	0.9	2.6	2.4
TES 4	0.6	0.9	0.8	3.5
TES 5	0.8	0.8	1.8	1.1
TES 6	0.8	0.6	3.1	1.8

All of the S4 optical modules uses aspherical lenses to improve the optical performance. In case of the aspheres, the azimuthal orientation of the wedge angle was determined during the alignment turning process by the usage of on-machine metrology. This provides the knowledge to align the aspherical lenses during the joining process to minimize the influence of the wedge angle /6/, /7/. The aspheres are centered on the reflex image just as spherical lenses. Afterwards, the run-out or the tilt error of the aspherical surface share is determined by non-contact measurements at the outer region of the lens. The method is based on previous research regarding the centering and alignment turning of aspheres /8/. Figure 3 shows the measurement setup using an optical distance sensor. After the alignment of the spherical portion of the lens, the turning axis rotates and a sinus shaped distance signal shows the remaining “aspheric tilt” that represents the inherent wedge angle of the aspheric lens. The orientation and the height of the tilt is documented and used in the later joining process for azimuthal orientation.

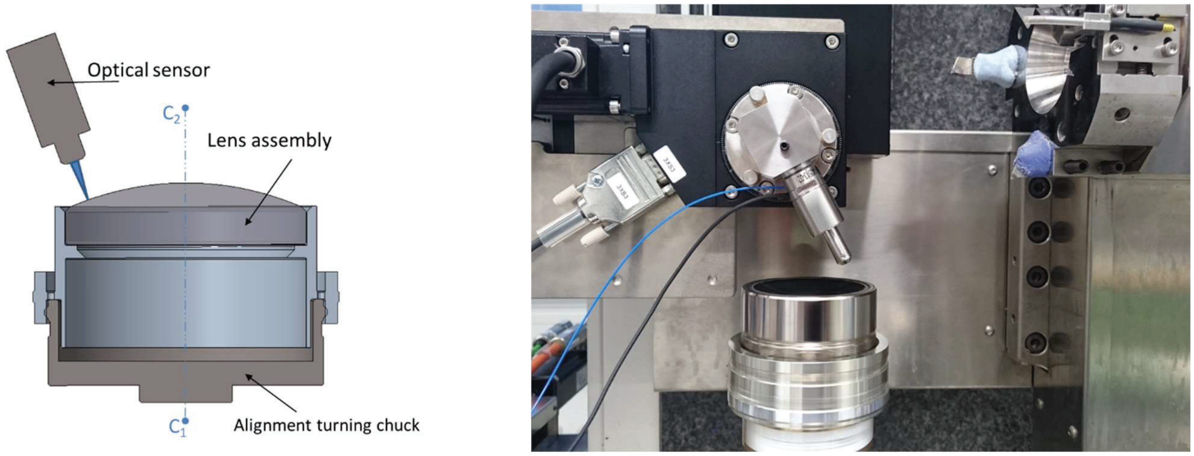
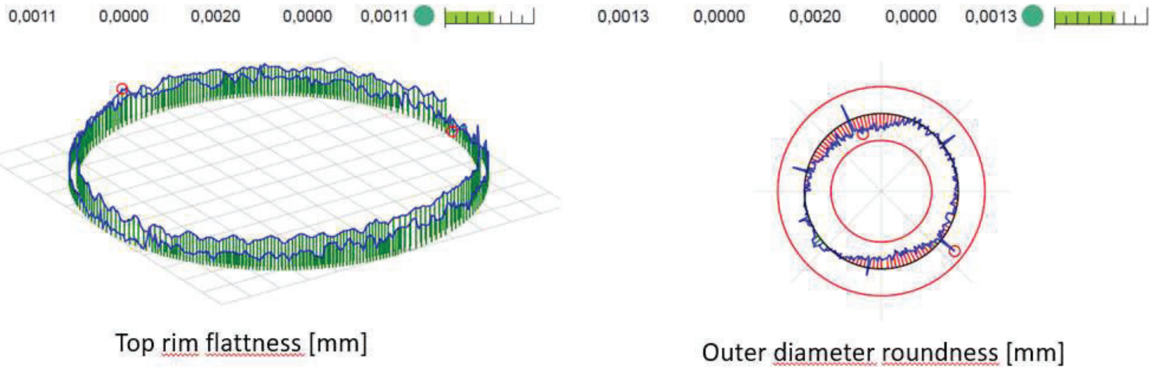


Figure 3: On-machine setup for measuring the wedge angle orientation of aspheres. Left: schematic representation, right: measuring lens 5 of the TOA optical module when turning the spindle.

In addition to the optimization of the cutting parameters for the housing materials used, an appropriate clamping of the lens assembly during the alignment turning process is essential. Deformations of the lens cell assembly due to the clamping on the turning chuck can influence the alignment turning quality by a spring-back effect after dismounting. To minimize the clamping effects, dedicated chucks were designed for the S4 lens assemblies. By providing a precise interface between the chuck and lens cell, the mounting distortions are minimized. This leads to single micron values for the roundness of the cell diameter and the flatness and parallelism of the cell rims. Figure 5 shows the measurement of the TES1-lens of the TOA proto flight model as a typical result.



Top rim flattness [mm]

Outer diameter roundness [mm]

Figure 4: CMM characterization of the TOA PFM, TES-1 lens housing after alignment turning.

2.2 Metrology of lens assemblies and iteration cycle

To establish a correction cycle for the alignment turning process as well as for characterizing the final status of the processed lens cell assembly, the parameters listed in table 3 have to be measured in sub-micron precision:

Table 3. Geometrical dimensions and parameters (refer to figure 2) of an alignment turned lens cell assembly and corresponding impact on centration

Lens cell assembly parameters

Parameter	***Purpose***	***Main impact on joined optics***
Outer diameter (D, Hüllkreis)	fitting to tube diameter	centration, lateral shift
Outer diameter, (R, roundness)	fitting to tube diameter	centration, lateral shift
Flatness and parallelism of rim (E1, E2, P)	adherend surface to next lens	centration, tilt
Height of rim (X)	lens positioning in Z direction	lens stack height, Z-position vs. tube
Vertex height (Y, Z)	surface distance in Z to next lens surface	air gap distance

The geometrical dimensions of the lens housing are derived by traditional CMM metrology under temperature controlled (T= 20°C ± 0.2 K) conditions. Considering a stress-free clamping and a discrete-point probing technique, a measurement uncertainty of 0.7 µm + L/400 and a probing uncertainty of 0.3 µm could be achieved. The investigations published in /9/ have shown that the acquired CMM data can be analysed to predict the final quality of the joined optical module.

The vertex height is measured by means of an ultra-precise 3D-profilometer UA3P Panasonic /10/, depicted in figure 5. Due to an extremely low probing force of 0.3 mN, it is possible to touch the lens vertex without leaving any influences on the optical surface. Combining the vertex height data with the results of the CMM measurements, the lens thickness is calculated and can be double checked with the numbers given by the lens manufacturer.

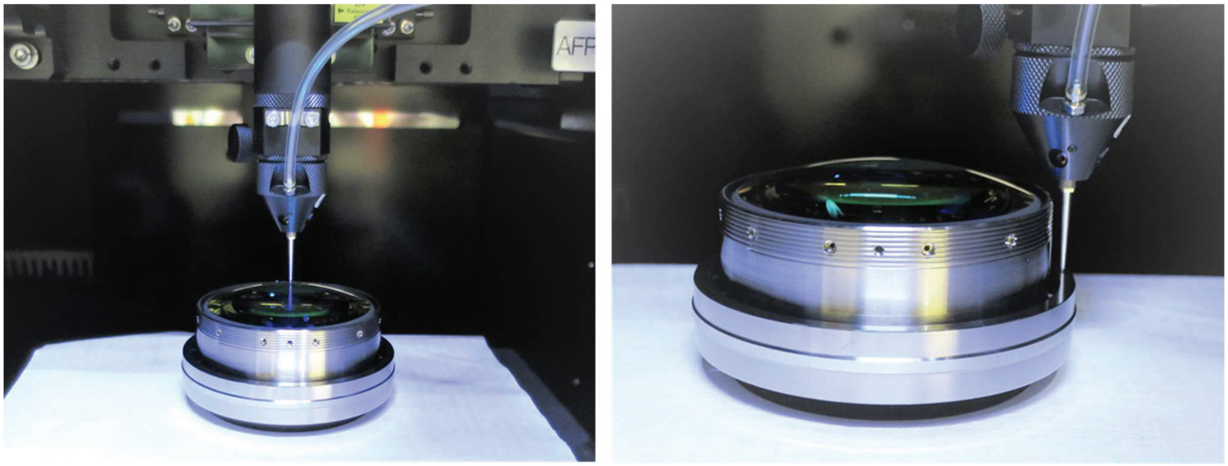


Figure 5: Measuring the vertex height of the NSA FM2, NIS 3 lens by 3D-profilometer UA3P. Left: Probing of lens vertex, right: probing lens cell rim

Usually the iterative machining of the lens housing takes place in three steps:

1. to cut free: realizing a housing geometry referenced to the optical axis,
2. rough cut: approaching the target dimensions but leaving a reasonable allowance, and

3. final cut: using dedicated turning parameters to the target dimensions.

After the first two cutting steps, the measured dimensions and parameters are feed back into the alignment turning process. This results in the basis to achive tolerances of less than 2 micrometers to the nominal housing dimensions. The characterization after the final alignment turning step provides as-built information of the lens cell assembly. The data are processed in an optics analysis tool to calculate the ideal housing dimensions and vertex heights for the following lens to be alignment turned. In this way, the entire lens stack is built up lens by lens.

2.3 Joining (drop-in assembly)

The proposed alignment turning technology relies consequently on the manufacturing precision of the lens housing references and the accuracy of the lens tube. Based on the acquired as-built data of all items and the known optical design, an analysis is carried out to verify the compliance of the realised lens set vs. the system requirements. As there are no further alignment or degrees of freedom foreseen, except of the azimuthal orientation of aspheres, the resulting prediction is highly confident and act as an approval for the joining process. The task of the joining process is solely the “drop-in” of the lens stack into the tube. The integration of the lenses in the tube is carried out with a mechanical mounting device (figure 6), developed for the S4 optical module assembly. The device consists of a flat granite base carrying a vertical Z-axis for holding and guiding the lens tube during the drop-in assembly. The passive joining process takes place as follows:

1. Mounting of the tube on the Z-axis.
2. Alignment of the tube relative to the mounting device coordinate system.
3. Build-up of the lens stack on the granite base plane.
4. Manually positioning of the lens stack in X and Y direction.
5. Inserting the lenses by movement of the lens tube vs. lens stack.
6. Protection and securing of the mounted lens stack by end ring, end caps.

The overall joining process is executed under ISO 5 cleanroom environment, whereby the cleanliness is monitored by particle (PAC) and molecular (MOC) process samples. The process duration including all steps mentioned above is less than two hours. The actual “drop-in” (step 5) lasts for only a few minutes. Compared to conventional integration and alignment techniques, the described method reduces assembly efforts and exposure time drastically.

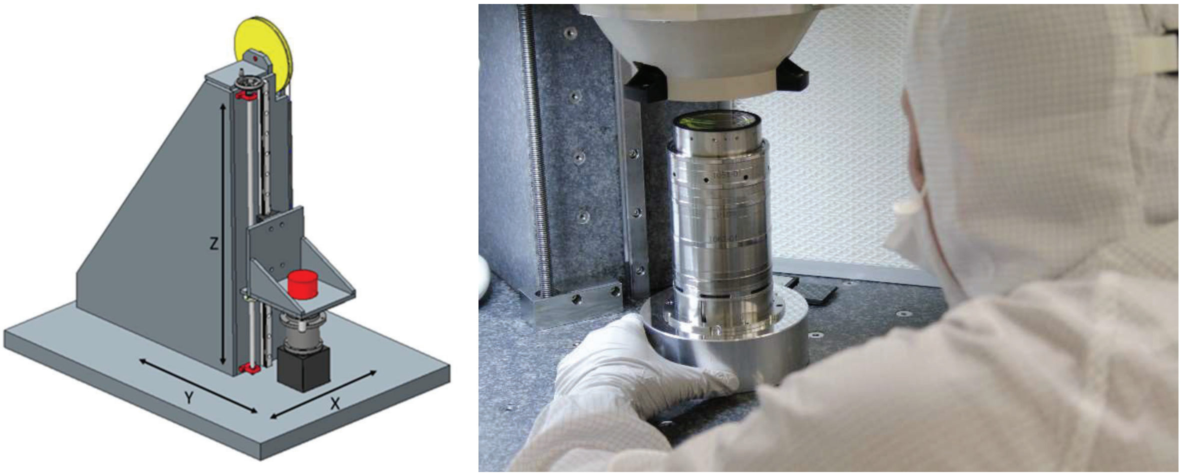


Figure 6: Joining process. Left: sketch of mounting device, Right: positioning of NSA PFM lens stack under the tube.

2.4 Clamping

The main task of the clamping process is to tense and lock the mounted lens stack into the tube by applying a defined axial force. The required clamping force is calculated by FEM simulations and ensures that the final position of each optical element, in particular the axial direction, is achieved and permanently fixed. Details of design and analysis approach are given in the overview paper /13/. Due to the usage of a dedicated spring ring element and considering the deformation behaviour of the module, the simulation can predict the force-displacement characteristics of the lens system. During the clamping process, the force-distance curve is determined by measuring the movement of the lens stack vs. the tube and compared to the calculated values (figure 9). Furthermore, the actual mounting gap at final pre-load is determined. This process is carried out by the usage of a clamping equipment (CGSE) outlined in figure 7. Mounted on the lens tube, the CGSE introduces the clamping force and distributes it to the lens stack. For each optical module (TOA, COL, CAM, NSA), a customized CGSE was developed and verified in an early project stage.

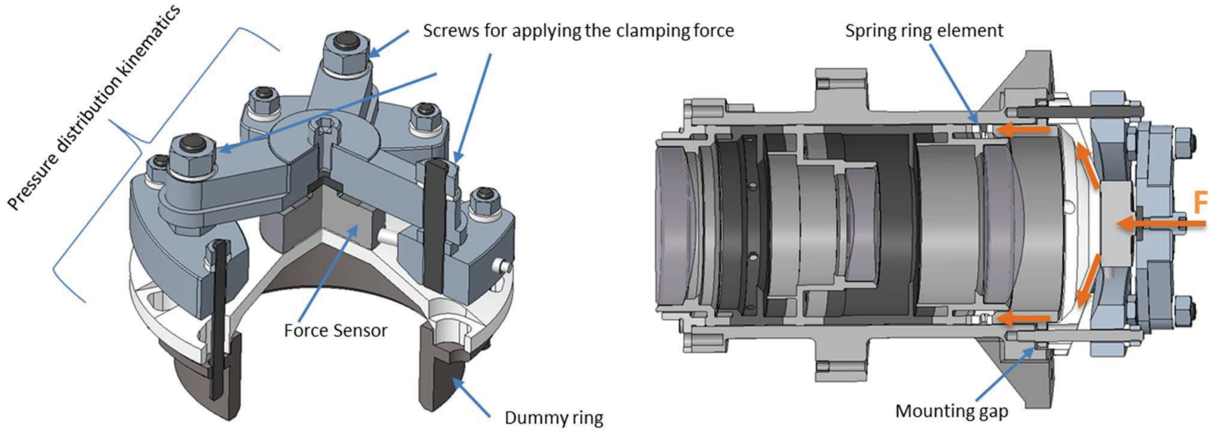


Figure 7: Clamping GSE for the Sentinel 4 NSA optical module, right: flux of the clamping force.

The clamping process is divided into sub-processes:

1. Clamping of lenses and tubes with the required tension and determining the mounting gap using a dummy ring.
2. Machining of the actual end ring in respect to the determined dimensions.
3. Clamping of lenses and tubes with clamping force using the adjusted end ring.
4. Locking of the system.

For the first step, the module is equipped with the CGSE and placed on a coordinate measurement machine (CMM). The lens stack is clamped by a dummy end ring, whereby the clamping force is introduced centrally into the system using a pressure point. It is distributed symmetrically on the lens stack via a pressure distribution structure. The clamping force is established gradually by screwing the three upper nuts and monitored by a centrically installed pressure force sensor. With the CGSE, the lens stack can be probed inside the tube trough openings in the dummy ring in order to measure the distance to the flange of the barrel under the defined clamping force (see figure 8).

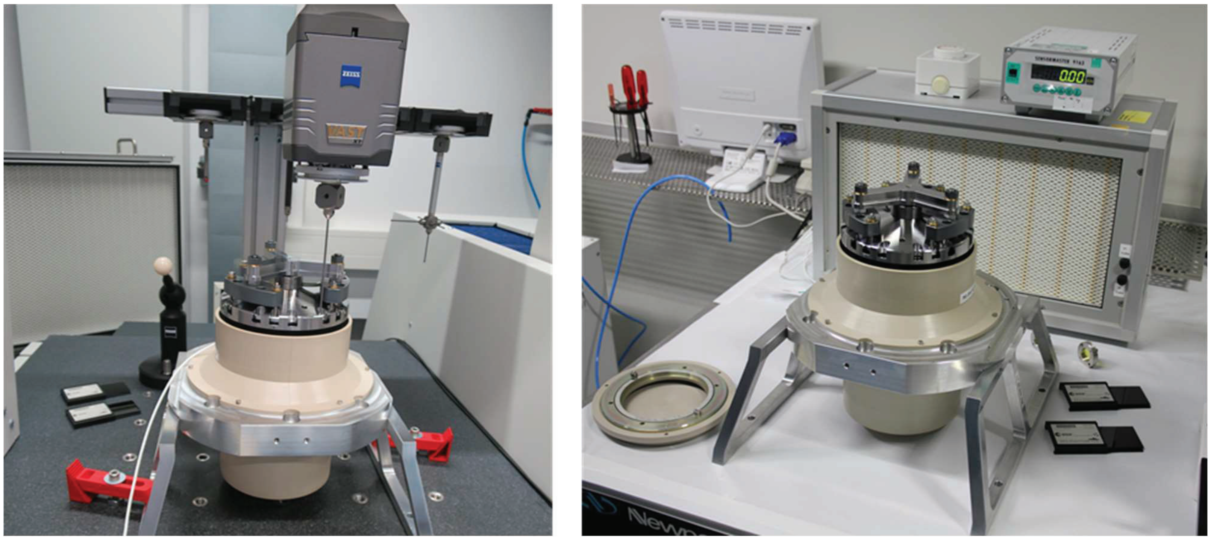


Figure 8. Clamping of the TOA-PFM optical module, Left: probing the lens stack in relation to the tube flange, Right: clamping setup for the final locking of the TOA-PFM

The measured distance is used to calculate the actual mounting gap at final pre-load to adjust the end ring of the module to the required dimensions by alignment turning (Step 2). Following the CGSE is used again for the final mounting of the lens stack with the defined and monitored pretension. For this process step 3, the dummy ring is replaced by the adjusted end ring (Step3). The applied pretension is introduced into the system and enables a force-free locking of the system.

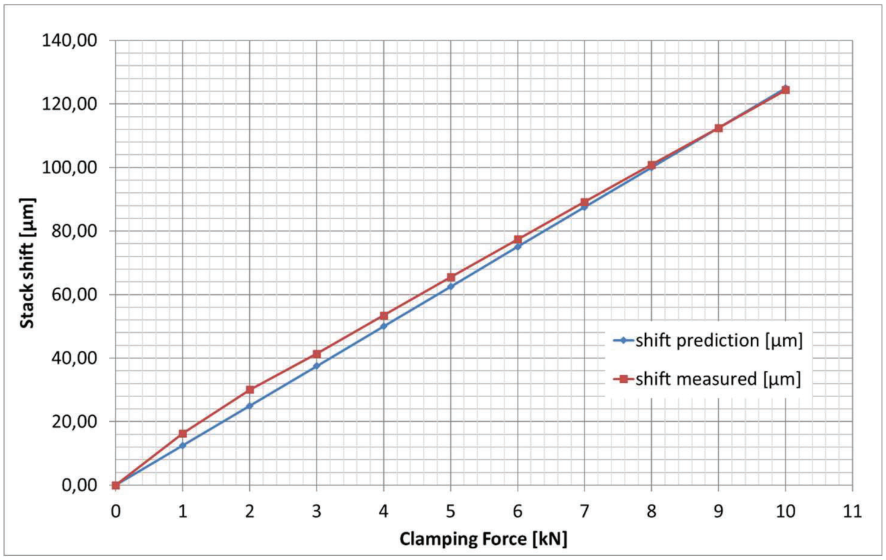


Figure 9. Comparison between calculated and measured lens stack shift during clamping of the COL-PFM.

3. RESULTS

The derived centration and Z-positioning of the alignment turned optical systems where observed using an OptiCentric 100 Dual 3D measuring system that measures the centring error of the surfaces of each optical element /11/. It enables the investigation of the X-position, Y-position and tilt of the individual lens with respect to the best fit optical axis of the lens system. The relative positioning of the best fit optical axis vs. the reference axis of the metrology system is analysed as well. The principal setup contains two measuring heads, which are basically autocollimator assemblies. The measurement of the centring error of the optical element surfaces is based on the rotation of the lens system and the observation of the reflected light. With the aid of a head lens, the light is focused on the centre of curvature of the investigated surface. If there is no centring error on the examined surface, a sharp and stable image of the reticle is projected onto the sensor. Otherwise the image describes a circle while the lens system is rotated. The radius of the detected run out circle is a measure of the centring error.

Additionally, the metrology setup is equipped with a low coherence interferometer that allows a non-contact center thickness and air distance measurement. Consequently, it enables the z-position determination of each optical surface.

Table 4 summarizes the centering errors of the lenses for the NSA-PFM optical module exemplary. Comparable results were achieved for the TOA, COL, and CAM modules. Looking at the achieved alignment status of the best fit optical axis of the lens system with respect to the reference axis of the measurement system a high process stability can be noted. All processed Sentinel 4 optical PFM and FM2 modules show a maximum shift of the best fit optical axis less than 3 µm and a maximum tilt ≤ 3 arcsec, respectively. The Z-positioning and air gaps were also realized in compliance to the requirement of less than 5 µm. A compact overview about the achieved optical performance and stability is given in /12/ and /13/.

Table 4. Measurement results of lens centration vs. best fit optical axis of the NSA PFM.

Shift and tilt errors of the optical elements w.r.t. the best fit optical axis (mean value from three measurement series).

Optical element	*Shift x [µm]*	*Shift Y [µm]*	*Tilt X [arcsec]*	*Tilt Y [arcsec]*
NIS 1	0.86	0.6	-2.29	0.44
NIS 2	-0.8	-0.5	-2.93	-3.09
NIS 3	0.74	0.13	0.36	0.01

4. SUMMARY / CONCLUSION

The alignment turning approach is successfully applied on the Sentinel 4 optical modules. Using a customized alignment turning machine, the decentration of the housed lens was detected and adjusted in respect to the turning axis. After machining of the housing, the vertex height as well as the geometry of the lens cell were measured in sub-micron precision. This provides the basis for the deterministic manufacturing loop of the lens housing with respect to the optical function of the lens. For the passive joining of the alignment turned lens elements in to the lens tube without further adjustment steps, a specific mounting device was realized. A newly developed clamping process, which ensures a dedicated pre-load, completes the assembly procedure. The alignment turned and assembled flight models were characterized using a centration measurement system. The alignment status of the optical axis of all individual lens systems in relation to the measurement reference axis as well as the Z-positioning were determined within the required specifications. Further optical verification measurements confirm the achieved optical performance of the optical modules to the full extent /12/, /13/.

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