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ASPHERICAL AND FREEFORM MIRRORS BASED ON ULTRA-PRECISE MANUFACTURING FOR TELESCOPES IN THE VIS SPECTRAL RANGE

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I. INTRODUCTION

In order to develop customized (freeform) optics, closed technology chains from design to system assembly are necessary and already established within the Regional Growth Core ƒo⁺[1]. Technology chains are available for metal optics and glass optics, while metal optics (mirrors) are used for reflective applications; brittle-hard glass optics and ceramics are used for reflective and refractive applications. Although the basic optical and mechanical design together with the analyses of parametrization of the optical surface, references, and kinematical mounting are nearly independent of the substrate material, the technology chains for manufacturing the individual components are significantly different from each other. These technological steps are essentially adapted to the structural properties of the used materials.
Diamond machining with servo-assisted techniques like slow tool servo (STS) or fast tool servo (FTS) allow the manufacturing of ultra-precise aspherical and freeform mirrors. The surface quality regarding roughness and periodic patterns, however, is limited to applications in the IR spectral range [2]. The combination of diamond machining with polishing techniques like magnetorheological finishing (MRF) or chemical-mechanical-polishing (CMP) enables the fabrication of surfaces with lower roughness, without periodical structures, and of high form accuracy [3; 4]. Such quality is suitable for applications in the visible (VIS) spectral range. A growing number of multi- and hyper-spectral imaging devices such as telescopes and spectrometers are based on reflective metal optics. The fabrication of metal mirrors with aspherical or freeform surfaces is an expanding field. Novel instrument studies of telescopes and spectrometers used more and more freeform mirrors like anamorphic shaped mirrors [5]. The properties of telescopes based on anamorphic mirrors are compact design, high accuracy, rectangular formed field of view, and wide angles [5; 8; 14].
The paper presents the fabrication of metal mirrors based on ultra-precision manufacturing. The discussion is focused on a combination of servo-assisted diamond turning and MRF polishing for the manufacturing of aspherical and freeform mirrors and arrangements of two mirrors on a common substrate, respectively. Finally, two optical system designs are discussed and results of an optical bench for an anamorphic telescope for application in the VIS spectral range are summarized.

II. ULTRA-PRECISE MIRROR MANUFACTURING

A. Single mirror

The ultra-precision manufacturing of aspheres became a major topic in the last 20 years, since modern optics achieve significant improvements through the transition from spherical to aspherical optics. The potential of using asymmetrical surfaces (freeforms) for generating further progress in optics has been promptly recognized. Ductile materials (metals) are usually ultra-precisely processed with monocrystalline diamond tools. For this being the only manufacturing step, a quality criterion of the optic is whether it is diffraction limited for long-wave IR applications or not. Typical values for form deviations are 6 µm p.-v. and 1 µm rms, respectively, as well as roughness values of 10 nm rms. For the spectral enhancement to applications in the visible spectral range down to 400 nm wavelength, combined diamond cutting and polishing methods have matured to key technologies at Fraunhofer IOF. In order to perform the mentioned polishing steps and ion beam figuring (IBF) after diamond turning an additional thick X-ray-amorphous layer is to be provided. Such X-ray-amorphous layers are preferably made of nickel-phosphorus, enabling the shaping with diamond tools [3; 6]. The values obtained for, e.g., an off-axis asphere of about 200 mm x 180 mm are form deviation of 140 nm p.v. and 18 nm rms, respectively, as well as roughness values of 1nm rms in the measurement field of 141 µm x 105 µm analyzed with white light interferometry (WLI, magnification 50x). Currently, the process combination of diamond turning techniques (SPDT) and magneto-rheological finishing is being implemented. Both the form of corrections and the roughness can be reduced by MRF polishing in one cycle. Typical values for freeform mirrors with a clear aperture (CA) of 250 mm diameter are differences in shape of 104 nm p.-v. and 12.5 nm rms (see Fig. 2), respectively, as well as roughness values of 0.8 nm rms (WLI, magnification 50x). By expanding the technology chain to a shape-retaining chemical mechanical polishing (CMP) step, the roughness of e.g. curved metal mirrors is improved to values below 0.3 nm rms for HSFR (High Spatial Frequency Roughness).

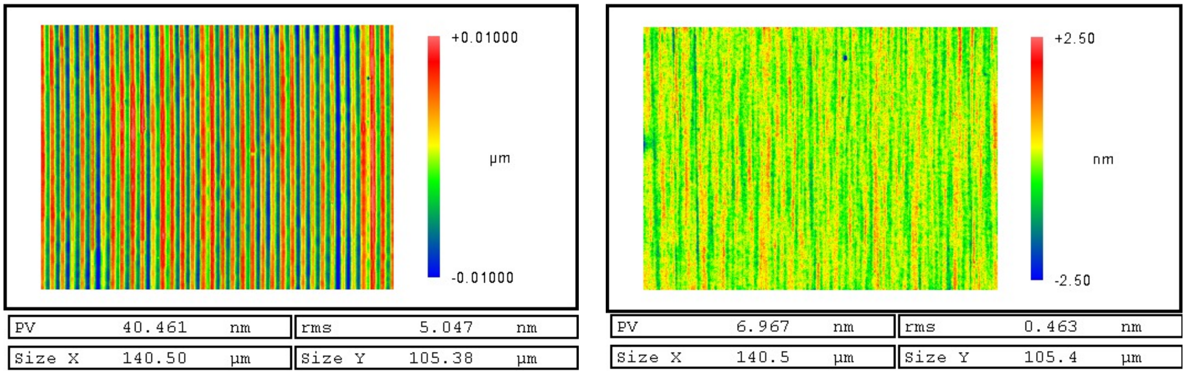

Fig. 1. Roughness of a metal mirror (magnification 50x; measuring range 141µm x 105µm); left: after diamond turning with typical pattern; right: after MRF polishing [8].

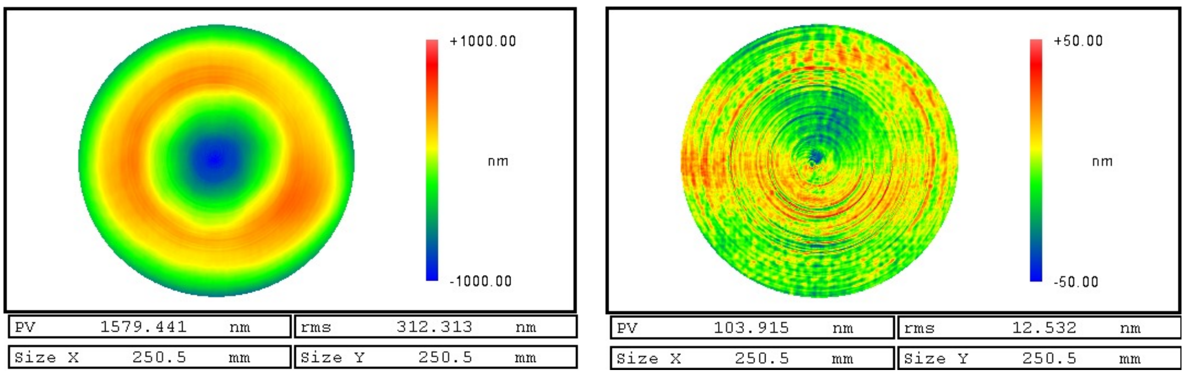

Fig. 2. Shape deviation of curved metal optics (diameter: 250 mm; freeform mirror with approx. 400 µm unsymmetry); left: after slow-tool diamond turning; right: after MRF polishing (three cycles).

The increased mid-frequency parts with spatial wavelengths of 0.2 mm to 2 mm that are associated with the diamond turning are limiting factors of the optical performance. Such frequency parts are not reducible by MRF polishing. Reducing the mid-frequency errors is possible by a further polishing step with laterally extended tools.

Manufacturing of optical surfaces with shape deviations below 100 nm p.-v. and 12 nm rms, respectively, as well as micro-roughness values of less than 0.5 nm rms (WLI magnification 50x) is possible by a deterministic process with further technological changes and enhancements. From this, systematic irregularities due to machine axes, radius transitions of the tools, and tensions caused by correction cycles with different tool types and foot print during processing are compensated. Such iteration for unsymmetrical geometries relies on the acquisition and compensation of the irregularity with the initial tool path of the processing machine. Due to hardly possible distinction between shape deviation and position error according to the required shape, the missing rotation symmetry prevents the unambiguous referencing of the component in the measuring machine (interferometer, 2½ D profilometer) for error feedback. Therefore referencing freeforms with reference marks, preferably small concave spheres at the margin of the mirror that are machined in one setting with particularly the same tool as the optical surface, has been established at Fraunhofer IOF [7; 8; 11; 12; 13; 14]. Those references can be examined in detail by sub-aperture computer-generated holograms (CGH) revealing shape deviation, information of the position, and radius of the optics as well [7; 8; 11; 13; 14]. Tailor-made CGH with lithographical quality and highest accuracy are realized as zero-comparators by electron beam lithography at Fraunhofer IOF.

In order to develop glass optics, the technology chain is complemented by further techniques like high-precise grinding and polishing. Optics with comparable qualities can be realized. As the processing tools cover a larger and variable surface area, especially the limitation by mid-frequency errors is significantly reduced. The quality level is actually defined by high-power optics like EUV optics.

B. Mirror module with two mirror surfaces on a common substrate

Processing and assembling of a freeform mirror requires particular attention of six degree of freedom (DOF). This renders the manufacturing effort of an unsymmetrical optical component enormous. Also scientific issues of measuring and referencing have to be included. The challenge can be solved by manufacturing two mirror surfaces on a common substrate. Due to the monolithic binding of both mirror surfaces, the degrees of freedom are reduced significantly during assembling. The increased requirements in terms of production, however, lead to advantages in the cost balance sheet as the mounting duration can be reduced from several weeks and months to a few days.

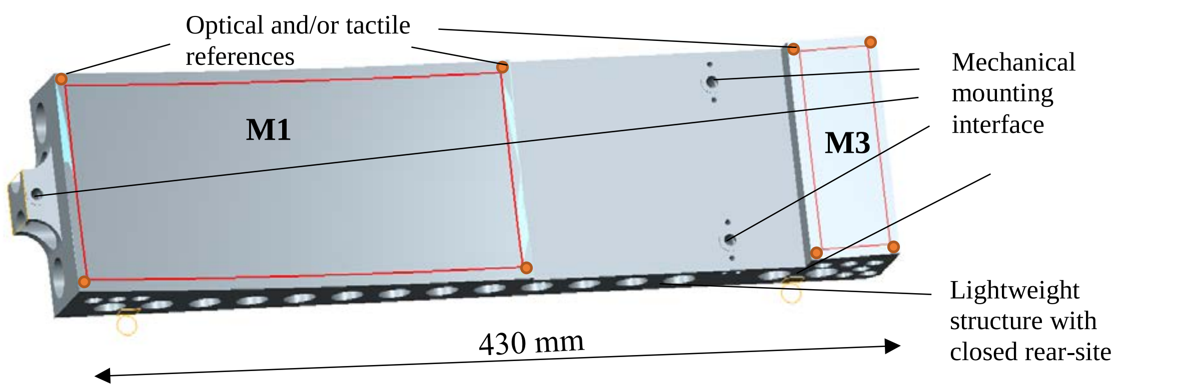

Fig. 3. CAD layout of the mirror module M1-M3 including the optical surfaces M1 and M3, ultra-precisely machined mounting interfaces, and reference spheres for tactile and/or interferometric metrology.

In case of processing and data handling of a mirror module, a very complex approach to manufacturing freeforms is to be followed [9]. During the design stage, several constraints must be fulfilled. The technology is based on the mathematical continuation of the two optical surfaces to a common freeform, at which reference points for a closed tool path are created in the free areas. The current limit of the available tool stroke of 6 mm in fast tool mode is an example for a production constraint. Furthermore, a strict synchronization of the tool position in Z to the angular position φ is required and the tool path is to be analyzed in terms of tool stroke and turning points particularly with respect to the acceleration of the tool (Fig. 4).

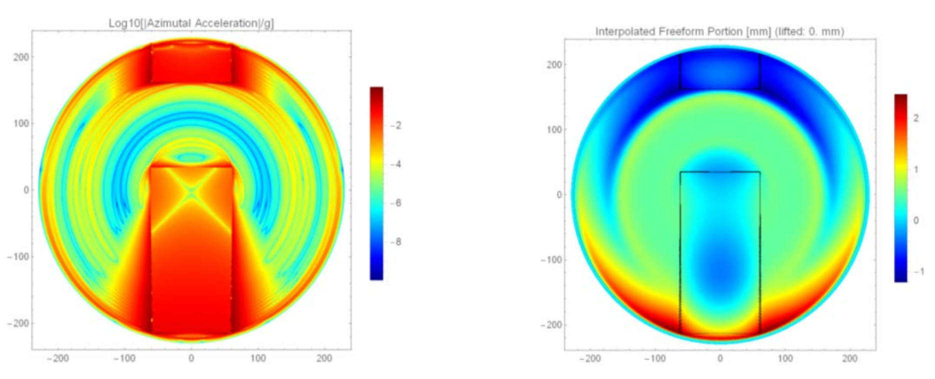

Fig. 4. Manufacturing analysis; left: azimuthal acceleration of the tool; right: freeform portion (equivalent to fast tool travel) for diamond turning of both optical surfaces in a single tool path for mirror module M1-M3.

After mechanical prefabrication, ultra-precise diamond machining of individual mirror substrates is performed. For low-stress joining of the substrate, an ultra-precise mounting device is used, while the fly-cutted very planar rear mirror side is then puttied on the device. The planarity of the substrates is essential for minimizing elastic tensions during bonding operation and for the shape accuracy after ultra-precise manufacturing of mirror surfaces. Based on simulations, the cutting period for UP machining of the module is calculated. Diamond machining occurs in combination of two manufacturing processes in the same machine setup, whereby the mirror surfaces are processed by diamond turning and the optical reference surfaces and mechanical mounting structures by diamond milling. Both tools were previously adjusted to an accuracy of significantly below 1 µm in case of the positioning precision. Optical and mechanical references exhibit optical reflecting quality, ensuring a positional reference to the mirror surfaces of about 1 µm accuracy.

Fig. 5. Manufacturing steps of mirror module; left: UP fly-cutting of rear site; middle: combination of diamond turning and milling in one setup; right: MRF correction with 50 mm polishing wheel [14].

Flatness examinations of the rear sides of the mirror module were performed interferometrical; the shape deviation is below 1 µm p.-v. Minor irregularities in the size of < 5 µm can be tolerated as they are compensated by the flexible adhesive gap. Influences of manufacturing stresses during diamond turning of the mirror modules are negligible. The characterization of the mirror surfaces with respect to each other and in relation to the reference surfaces can be done tactile or optical. After interferometric metrology with a CGH of the mirror surface, a null test of a mirror module can be realized as well (see Fig. 6 right). The development of the CGH is based on the structuring by electron beam lithography and besides, the measurement depends on the deformation of the CGH substrate (used in transmission) and on the interferometer as well as its reference. At Fraunhofer IOF a reference with an accuracy of λ/30 @ 633 nm which is equal to 21 nm is achieved. The accuracy of the technical analysis has an uncertainty of ± 30 nm p.-v. For mirror modules with large mirror substrates, it might be necessary to use one CGH for each mirror surface.

For the metrology of the mirror modules, all surfaces are measured by 2 1/2-D profilometry on a Panasonic UA3P 650H with respect to minimum four metrology fiducials on each mirror (see Fig. 6 left). The large measurement area of 400 mm x 400 mm x 120 mm in combination with a measurement accuracy of ± 50 nm p. v. enable measuring of all surfaces and fiducials highly accurate in a common coordinate system without moving the part. After pre-aligning the mirror in the measurement device, both optical surfaces are scanned with a diamond stylus exhibiting a radius of 5 µm in a meander-shaped pattern in two orthogonal directions. Furthermore, all reference points are measured and their coordinate positions are registered.

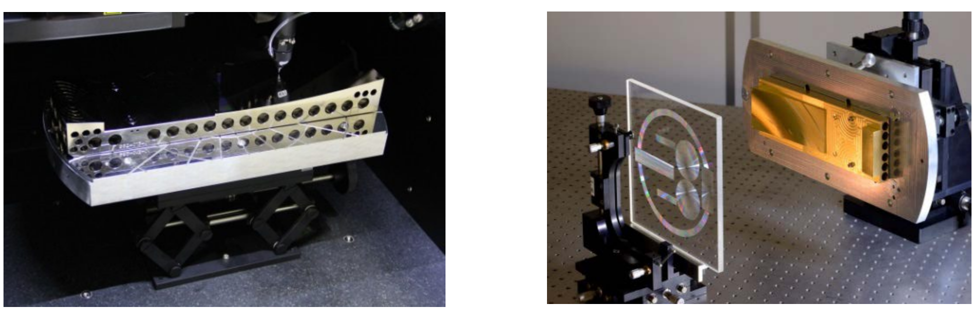

Fig. 6. Measurement of the mirror module in the profilometer UA3P 650H from Panasonic with a 5 µm diamond stylus at Fraunhofer IOF (left); measurement setup with multi aperture CGH for a smaller mirror module, sample from PREMIER instrument (right) [5; 8; 10; 13].

For smoothing and shape correcting, the mirror modules are processed by fast-tool diamond turning in combination with MRF polishing. Typical correction values of the MRF processing are below 2 µm. The iterative processing has been performed with polishing wheels of different sizes (370 mm and 50 mm, respectively, in diameter).

Deviations of less than 1 µm p.-v. with respect to the designed shape can be reliably achieved by corrective machining with the FTS technology of the diamond cutting method (see Fig. 7). Primarily, remaining differences are the result of thermal fluctuations in the machine environment during the final ultra-precision cut. Nevertheless, the shape deviations of the individual surfaces do not meet the requirements of high-quality imaging mirror optics in the visible spectral range. The following MRF processing step reduces the shape deviations of individual surfaces (see Fig. 8). The corrective machining enables the reduction of the shape deviation down to 15 nm rms for freeform surfaces geometries; the relative position deviation is less than 1 µm.

After MRF polishing, micro-roughness values are within 0.5 nm and 2 nm rms (WLI magnification 50x, measuring range 140 µm x 105 µm) depending on the polishing suspension used.

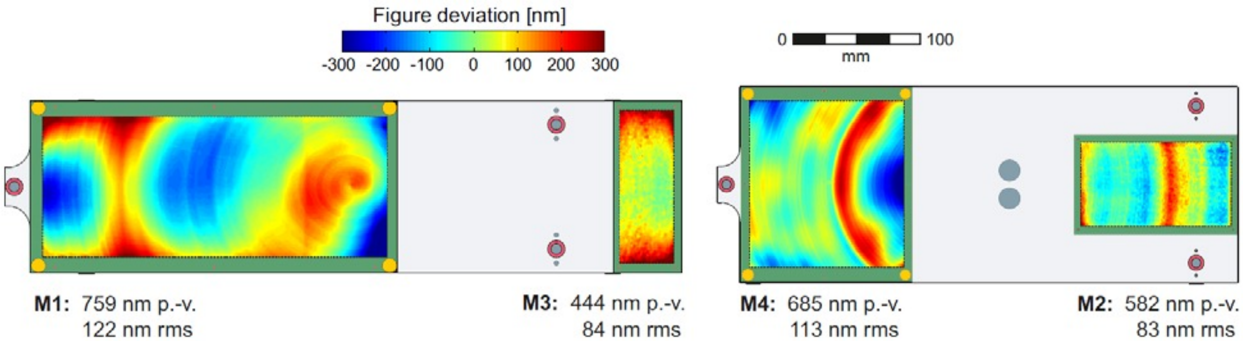

Fig. 7. Shape- and relative position deviations of the mirror modules M1-M3 (left) and M2-M4 (right) after ultra-precise diamond machining [14].

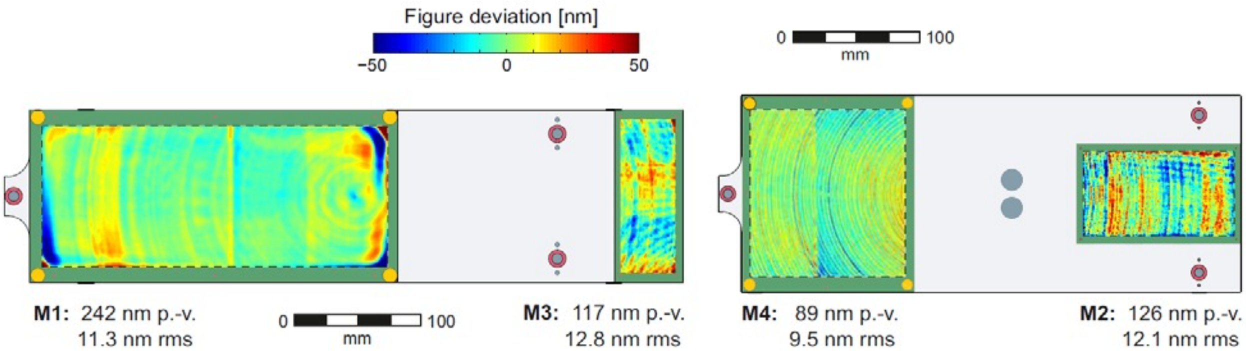

Fig. 8. Shape- and relative position deviations of the mirror modules M1-M3 and M2-M4 after MRF [14].

III. OPTICAL AND MECHANICAL DESIGN OF TWO TYPICAL INSTRUMENTS

A. Bread board of a TMA telescope demonstrator - fo^{+} [freeform optics plus]

For the growing market of spaced-based Earth observation, a freeform metal mirror system is developed within the Regional Growth Core fo^{+}. It is designed in an athermal manner for hostile environment conditions with improved optical properties compared to the state of the art. Due to novel manufacturing, alignment, and integration techniques reaching a technology readiness level (TRL) of 5, production costs are reduced.

The optical system consists of four metal mirrors, where three of them are freeforms described by an asphere in combination with Zernike polynomials. The fourth mirror is a plane mirror to fold the rays and reduce the size of the housing. All three freeform mirrors share a common optical axis; the optical stop is located at the mirror M2. The effective focal length is 325 mm; the f-number is F/4. Further, the optical performance is MTF > 60 % at 100 lp/mm and the distortion is 2.9 %.

For thermal and mechanical verification of the CAD model, finite element analyses were performed. These include modal analyses, structural analyses, and temperature loads and are used to optimize the model according to space qualifications. The final model has a mass of 13.8 kg without bolts, including 1.6 kg FPA. Fabrication is done by using voice coil driven fast tool servo of an ultra-precision turning lathe. This tool tolerates accelerations between 0.2 g and 7.5 g corresponding to a turning frequency of less than 30 rpm. Furthermore, the tool stroke is limited to be between +/-3mm. As a key point of the fabrication cycle, turning and milling are performed in the same setup. For correction steps during ultra-precision machining phase and final test as well as integration, optical (interferometric) and tactile measurements are performed.

For mounting and aligning, the snap together approach is utilized in order to fix most of the 24 DOF during the ultra-precision manufacturing stage [11; 12]. The mounting concept leads to the necessity to align six DOF. Since both mirrors M1 and M3 are fabricated on a single substrate, a necessary condition is to reduce the freeform tool stroke and the corresponding tool acceleration. Thus, the respective curvature radii of M1 and M3 have to be similar. In this context, it is a major advantage that all freeform mirrors are described in relation to a single optical coordinate system, i.e. the common optical axis. This leads to a simple data flow throughout the process chain as there is only one coordinate transformation between optical and manufacturing coordinate system required.

Using an optimized data flow developed within fo^{+}, a CAD model for the freeform mirror system was created (Fig. 9). The athermal mechanical design is achieved by material combinations: NiP layer and AlSi42 substrate for the freeform mirrors, Al6061 and ultra-thin Si coating for the folding mirror as pre-test of a new material combination, AlSi42 for the housing, and 1.4462-stainless steel for the bipods.

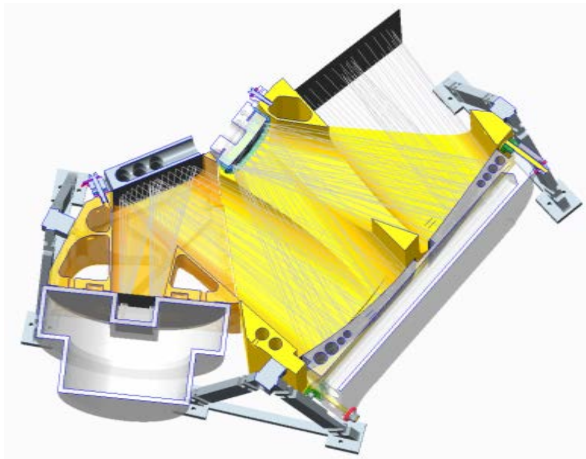

Fig. 9. CAD model of the complete TMA including FPA dummy at the left hand side, the bipods (left and right hand side of the M1-M3 substrate between FPA dummy and M2 mirror), ray bundles, and mirror intersection.

B. Four mirror anamorphic telescope; demonstrator for a bread board instrument VISTEL

The optical design uses four anamorphic mirror aspheres for an afocal image. The entrance pupil with a rectangular aperture of 200 mm x 50 mm is imaged on a square output pupil with an aperture of 70 mm x 70 mm. The maximum field angles are ± 3.22° in transverse and ± 0.47° in longitudinal direction. The telescope is suitable diffraction limited in four field points for test wavelengths of 632.8 nm and thus, it is applicable as front optics for beam shaping, e.g. for camera optics. In order to correct field-dependent aberrations, the individual mirrors are tilted in one direction against the position of the entrance and output pupils.

The optical surfaces are defined among each other regarding a common coordinate system, enabling the design of two optical surfaces on a common substrate as well as processing of two optical surfaces as a monolith by UP machining (see Fig. 3 and Fig. 5). Table 1 shows the geometrical parameters of the individual mirrors without higher coefficients of the aspheres.

Table 1. Geometry parameters of the individual mirrors of the telescope demonstrator.

Parameter	Mirror M1	Mirror M2	Mirror M3	Mirror M4
Radius X [mm]	-812.3	-4654.3	-2543.0	1580.3
Radius Y [mm]	-1182.4	-1155.0	-1046.0	697.6
Conic X	0.763758	0	0.680632 E+02	-0.659185 E+01
Conic Y	-0.456805	-0.605354 E+02	0	-0.493005 E-02
Aperture X [mm]	102.8	64.2	110.0	132.8
Aperture Y [mm]	217.9	107.2	30.1	108.7
Off-axis Decenter in Y [mm]	-238.9	-81.9	38.8	152.2

Due to the afocal design, the system performance can be examined directly via the transmitted plane wavefront using interferometry. The mechanical design is given in Figure 10 (left). For construction, two mirror modules with two mirror surfaces each, M1-M3 and M2-M4, respectively, are used. The surface export of the mirrors is done by the optics software ZEMAX. Based on this export, solid mirror modules are modeled. Both modules are connected with the building structure by using three ultra-precisely produced contact surfaces. The mechanical surfaces are processed in the same work step as the optical surface in order to minimize lateral deviations and tilts. Mirror body and telescope housing are made from space-certified Al6061 T6. The mirrors are connected to the housing via UP processed joint structures by means of bipod. Due to the ultra-precisely machining of all assembled joint structures, the air gap of the mirror modules M1-M3 and M2-M4, respectively, is fixed simultaneously within a few microns.

Both mirror bodies are realized in lightweight construction. For this, material from the area of the neutral axis has been removed by means of bores. Due to its contribution to a high stiffness, the base area (back side) remains closed. Introducing cross-drilled holes, a lightweight quantity of about 40 % compared to massive full bodies has been achieved. The module with basic dimensions of 430 mm x 110 mm x 50 mm reached a mass of approximately 2.65 kg including a 50 µm thick polishing layer of amorphous NiP.

The telescope housing is realized as a box with frame work type stiffening in two half-shells, while both half-shells are pre-processed separately. The stiffeners are designed in this way in order to enable maximum stiffness of the whole telescope under static and dynamic loads. Furthermore, the housing is conceived symmetrically and optimized for lightweight construction as well. In case of connecting the housing to other support structures, an isostatic mount is provided at three points (see Fig. 10). For system assembling, the snap together technology has been used [14]. The actual system analysis of the telescope has been conducted interferometrically in a double pass, measuring the wavefront with high-precision reference mirrors.

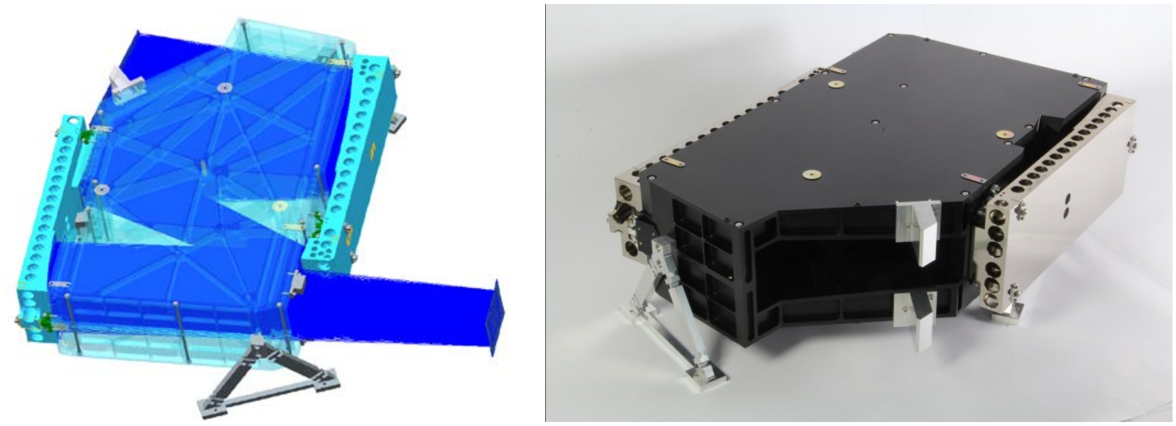

Fig. 10. CAD model of the complete telescope (left); final telescope demonstrator (right) [14].

The assembly has been realized by ten relative adjustment increments within a few hours; it verifies the concept of the simplified integration of visually imaging telescope optics. Figure 11 shows a comparison of theoretically calculated (Fig. 11A) and experimentally derived wavefront errors (Fig. 11B) of the anamorphic telescope demonstrator in the central field position. The wavefront error obtained in the output pupil is about 83 nm rms and thus, it is a factor of 1.9 higher than the nominal wavefront error of 43 nm rms [14].

The square rms wavefront deviation is dominated by a defocus term, which cannot be neglected considering the afocal system character. Thus, the system operates diffraction-limited from an application wavelength of 1.1 µm (NIR) according to the criterion of Maréchal.

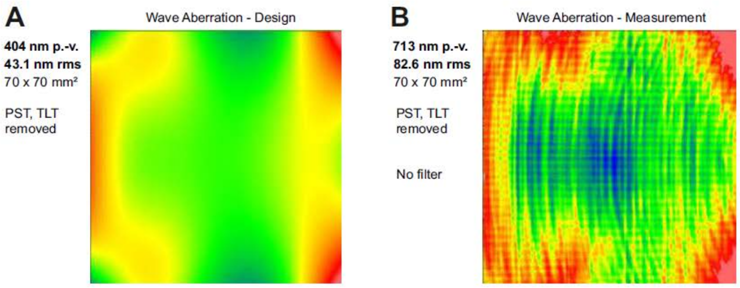

Fig. 11. Experimentally determined system wavefront of the anamorphic telescope in the central field point, A: designed wavefront 404 nm p.-v. / 43 nm rms; B: measured wavefront 713 nm p.-v. / 83 nm rms [14].

IV. SUMMARY

Increasingly, freeform optics influence the trend of developments in modern imaging high-power optics. Ultra-precise machining combined with MRF polishing turned out to be an excellent tool for producing reflective freeform optics (individual mirrors) or mirror modules with two optical surfaces applicable in the visible spectral range. Regarding mid-frequency errors, limitations still exist. Due to the combination of ultra-precise diamond turning and milling in a common setup, high accuracies in shape and position (< 1 µm) of the optical surface (typically < 15 nm rms) and of reference surfaces as well as interface structures are ensured, achieving requirements for a simplified mounting. The snap-together approach has been proven successfully by mounting a telescope with four freeform mirrors within a few hours, exhibiting a system performance of 713 nm p.-v. and 83 nm rms, respectively. Metal optics based on freeform components may be fabricated and mounted deterministically. They expand the technological portfolio of developing next generating telescopes for Earth observation and planet missions.

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