DESIGN AND FABRICATION OF A MINIATURIZED METALLIC TELESCOPE FOR EARTH OBSERVATION

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ABSTRACT

This article is about the development, manufacturing and characterization of a metal three-mirror-anastigmatic telescope (TMA) used for precise thermal Earth observation at the International Space Station (ISS). By utilizing well-known principles for high performance optics, like the "snap-together" technique, fabrication of two optical surfaces on a common mirror substrate or diamond-turning the described instrument shows how to effectively realize cost efficient, but still high-performance optical instruments based on freeform technologies. An overview of the process chain of the manufacture of metal-optical components is presented, followed by the design of the optomechanical components as well as the integration and mounting concepts. The advantages of metallic mirror systems in the context of the small satellite market and therefore as a serious alternative to classical refractive systems are presented.

1 INTRODUCTION

For many years, there has been an increasing trend in the miniaturization of classic satellites to miniaturized satellite systems [1]. They have the advantage of substantially lower overall costs for performing entire space missions [2]. For this reason, there has been a notable increase in the number of miniaturized satellites put into operation throughout recent years, especially for Earth observation. Finding answers to climate change is one of the main objectives of ConstellR GmbH. They are striving to monitor the water balance of the globe with microsatellites, and to use this information for high-precision agriculture, yield forecasting, sustainable resource management or disaster monitoring [3]. Therefore, they need a reliable, compact and high-resolution telescope optic to demonstrate their core technology on a demonstrator mission at ISS. For this purpose, a consortium consisting of the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF) and Fraunhofer Institute for High-Speed Dynamics (EMI) and their spin-off companies Spaceoptix GmbH and ConstellR GmbH was formed. In the next step the optic can be further developed into an optic for small satellites, which then enables daily coverage as well as global surface data. Due to the compact design of the available space at the NanoRacks External Platform (NREP) as well as in the planned satellite platform, there are strong restrictions for the payload, especially for the optical instrument. For example, the available space, the maximum weight, and the requirement for a very cost-effective production. Because of this, classical design approaches for optical systems reach their limits due to the fact of many simultaneous requirements [4]. To develop such high-performance optical systems with low costs for the New Space market, it becomes more imperative to find simple integration methods that can be employed in series production.

2 DEVELOPMENT AND MANUFACTURING CHAIN OF MIRROR SYSTEMS

There are several examples of high-performance optical systems on a big scale, such as DESIS or GALA (Figure 1). In previous Fraunhofer Institute for Applied Optics and Precision Engineering (IOF) publications, we have already discussed the advantages of metallic mirrors for such large and mid-size high-performance optical instruments. In this paper, the topic is presented from the point of view of small-size optical systems.

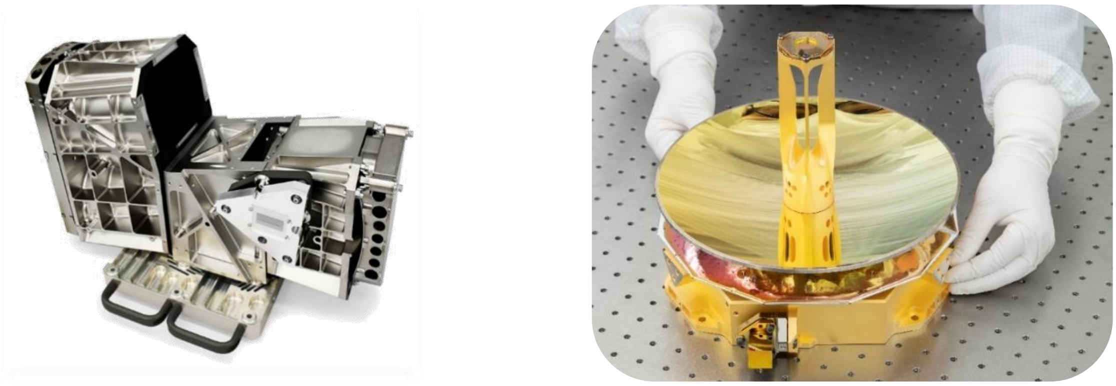

Figure 1. DESIS instrument (left, behalf of DLR) and GALA-Receiver (right, behalf of HENSOLDT Optronics), which were completely developed, manufactured and characterized at Fraunhofer IOF in Jena.

2.1 Metal mirrors for optical applications in miniaturized satellites

In general, a metallic mirror is built out of a mirror substrate and an optical coating, which is especially adapted to the intended wavelength range. Typical brittle materials for mirror substrates are glass, ceramics or glass-ceramics (a. o. Fused Silica, ULE or Zerodur), while ductile materials like metals are also used [5, 6].

Brittle materials are very sensitive to vibrations, which are transmitted from the satellite to the instrument. Negative effects of low-frequency vibrations or thermal gradients, e. g. mechanical damages as well as loss of optical performance, can be reduced by a decoupling structure between the mirror and the next higher system level (e. g. instrument housing). A key aspect of the development of high-performance optical instruments for small satellites is the efficient design in terms of its dimensions and weight, without compromises in optical performance. When classical materials are used for mirror substrates, decoupling structures prove to be a major obstacle to these requirements. Furthermore, mirror substrates of brittle materials are often integrated into the instrument with additional metallic mounting. This makes an additional transfer from the optical coordinate system to the mechanical coordinate system of the mounting necessary. The resulting tolerances are typically an order of magnitude higher than the achievable tolerances with micromachining. When using mirror substrate materials with a higher modulus of elasticity and low weight, the decoupling structures can be made smaller and thus more efficient overall. [7, 8]

The standard material for metallic mirrors is the aluminum alloy EN AW-6061 (AlMg1SiCu, 3.3214). The general benefits of this material are its high long-term stability, its low density, and its high reflectivity over a wide range of wavelengths. In terms of manufacturing, aluminum has the advantage of very good machinability and a long tool life. This makes it possible to use ultraprecise manufacturing methods like diamond turning (DT). This further enables the fabrication of rotational symmetric forms like spheres and aspheres, as well as non-rotational symmetric forms like off-axis aspheres and freeform surfaces with a shape deviation Peak-to-Valley (PV) smaller than 200 nm (surface diameter < 100 mm) and micro roughness in the range of RMS < 1 nm. [5, 6, 9, 10]

Nanosatellites are primarily launched into low earth orbits (LEO) and therefore many thermal cycles during their lifetime are expected. In terms of temperature sensitivity, optical instruments are one of the most delicate components [11]. They need to be designed in such a way, that no mechanical damage can occur. In addition, the optical performance should not be affected by changes in temperature. Although aluminum generally has a higher coefficient of thermal expansion ($23{,}6 \cdot 10^{-6}\ K^{-1}$), all components expand proportionally with a change in temperature, which means that athermal system properties can be achieved [12, 13, 14]. This means that temperature changes in a specific range have no influence on the imaging quality of the system. However, this simplified statement is only valid for small temperature intervals in which constant thermal expansion coefficients can be assumed. Furthermore, the improved thermal diffusivity minimizes the temperature gradients in the instrument, which is particularly important in the case of asymmetrically constructed instruments or components [15].

2.2 Simplified process chain of the manufacturing process

In addition to the actual development process as well as the functional and integration concept, the process chain for manufacturing a high-performance optical instrument represents a significant success and cost factor for the implementation of such instruments for the small satellite market. A series of optical instruments is more expensive to develop because it entails a more substantial amount of development work. An example is that the design must enable efficient manufacturing and the integration concept must facilitate fast, yet reliable, integration of the system. The costs are recouped with the increasing number of systems realized. This requires a suitable, reliable and in particular cost-efficient process chain. The latter becomes especially relevant when developing instruments for a constellation of satellites. In an ideal case, the processes have been optimized to the point where they are suitable for volume production. It was already discussed in earlier papers how to fabricate a single mirror and housing out of metal [7, 9, 10, 16]. In general, the process chain as simplified illustrated in Figure 2, is capable for series production. The Fraunhofer IOF spin-off Spaceoptix GmbH wants to specialize in the series production of high-precision optical components and systems for use in space, astronomy and industry. Therefore, they are currently commercializing this process chain for the New Space market. For the manufacturing of metal optics with high precision regarding shape and roughness it is necessary to apply the overall process chain shown in Figure 2. In addition, the simplified development and integration phase is shown. Depending on the application and spectral range of the instrument, not all fabrication steps are necessary.

As soon as the substrates have been mechanically prefabricated and given a first thermal treatment, an ultra-precise diamond turning process is performed. There are two steps involved in this manufacturing process: the optical surface as well as the mechanical interfaces are machined in optical quality, ensuring a positional reference to the mirror surfaces of about 1 µm. The advantages of a common fabrication of mechanical and optical references are discussed later in this article. Diamond machining allows the manufacture of ultraprecise mirrors, but the surface quality limits their use to the infrared (IR) spectral range due to the achievable roughness and resulting periodic patterns. By incorporating polishing techniques like magnetorheological finishing (MRF) and chemical mechanical polishing (CMP) after ultra-precise manufacturing, it allows fabrication of mirror surfaces with a wider spectral range. A lower roughness can be achieved without periodic structures, resulting in improved form accuracy [17].

As soon as the surface is in specification, an optical coating is applied. Over time, the Fraunhofer IOF has developed its own selection of different optical high-reflectivity coatings (HR-coatings) for different applications. Likewise, the coating processes can be completely done in house. After the manufacturing phase of the components, the integration phase of the system starts. An example of how this is demonstrated is given in chapter 3.4 and 3.5.

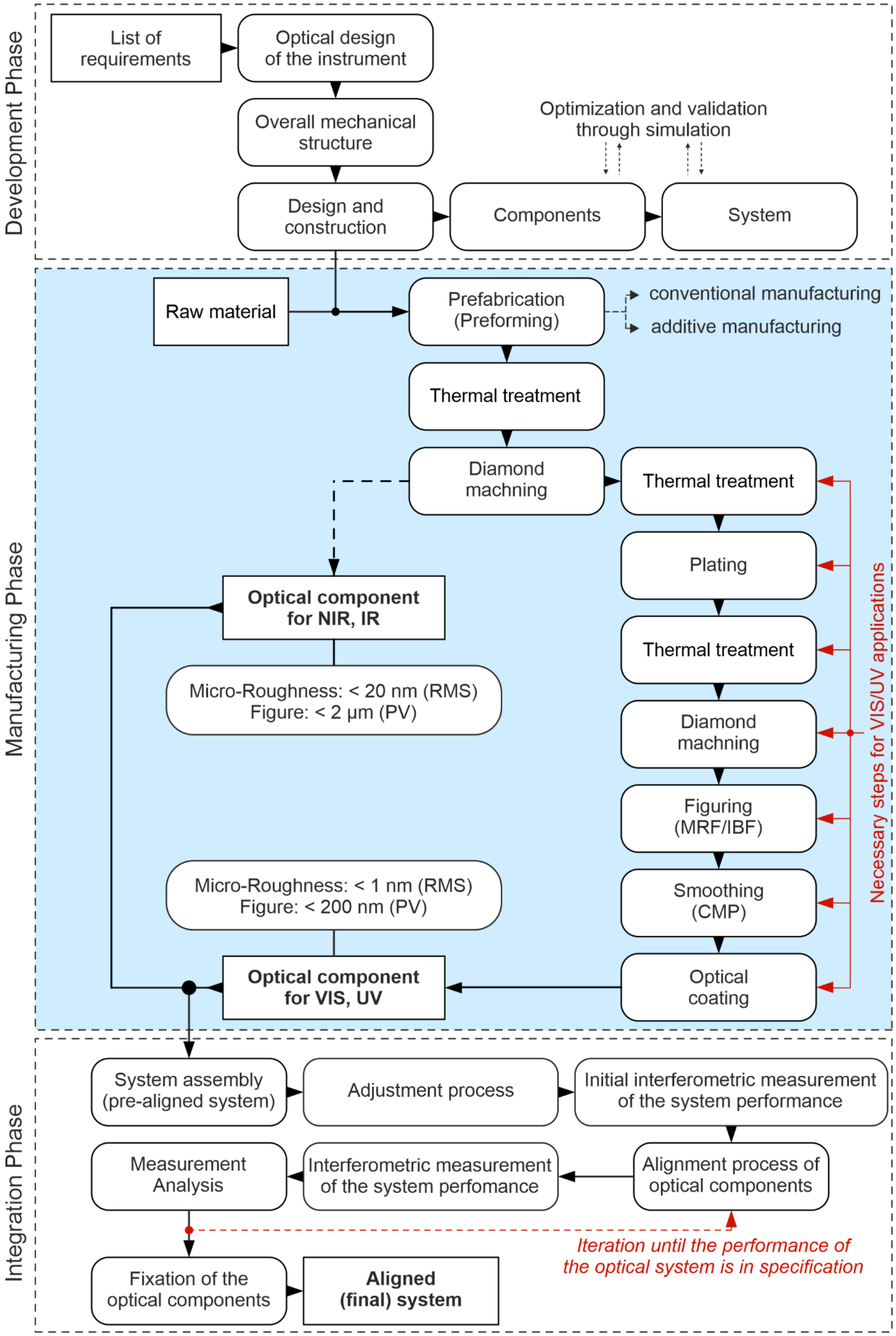

Figure 2. Simplified flowchart of the development, fabrication and integration steps for an optical instrument

3 OPTOMECHANICAL DESIGN OF THE INSTRUMENT

Figure 3 shows the manufactured and integrated mirror telescope for Earth observation. The whole system relies on metal-based mirrors. In this case, this scientific instrument was built for a technology demonstration at the NREP platform at the International Space Station (ISS) for the described use case at the beginning of this paper. The instrument development of LisR (Long Wave Infrared Demonstrator) and overall system integration was led and done by Fraunhofer EMI and ConstellR GmbH. The opto-mechanical design of the telescope was done by scientists and engineers at Fraunhofer IOF in Jena. Meanwhile, the production of the mirrors, the telescope structure as well as the mechanical structural components of the opto-mechanical total payload was done by Spaceoptix GmbH.

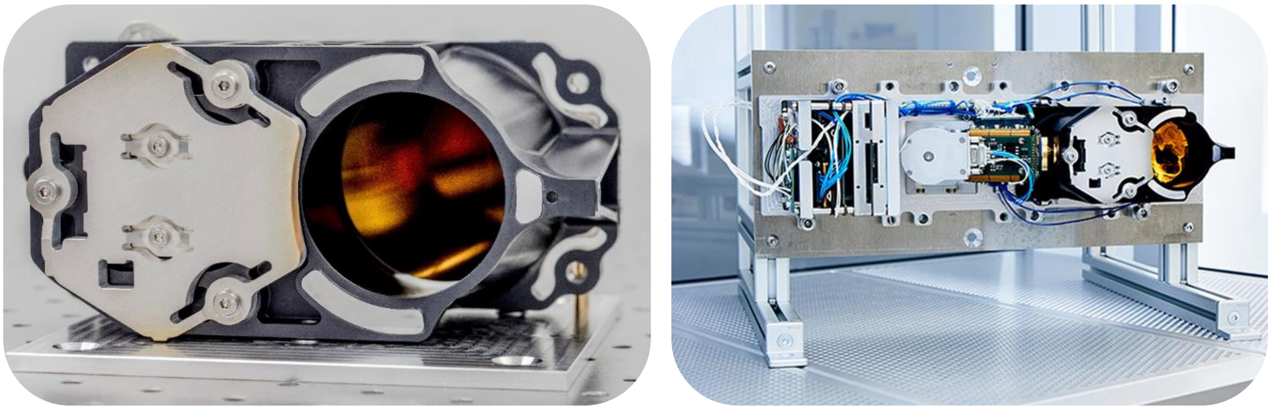

Figure 3. Left: Full aluminum mirror telescope for earth observation in the infrared spectrum (built for ConstellR GmbH); Right: Integrated telescope with sensor as well as command and data handling (C & DH) [18]

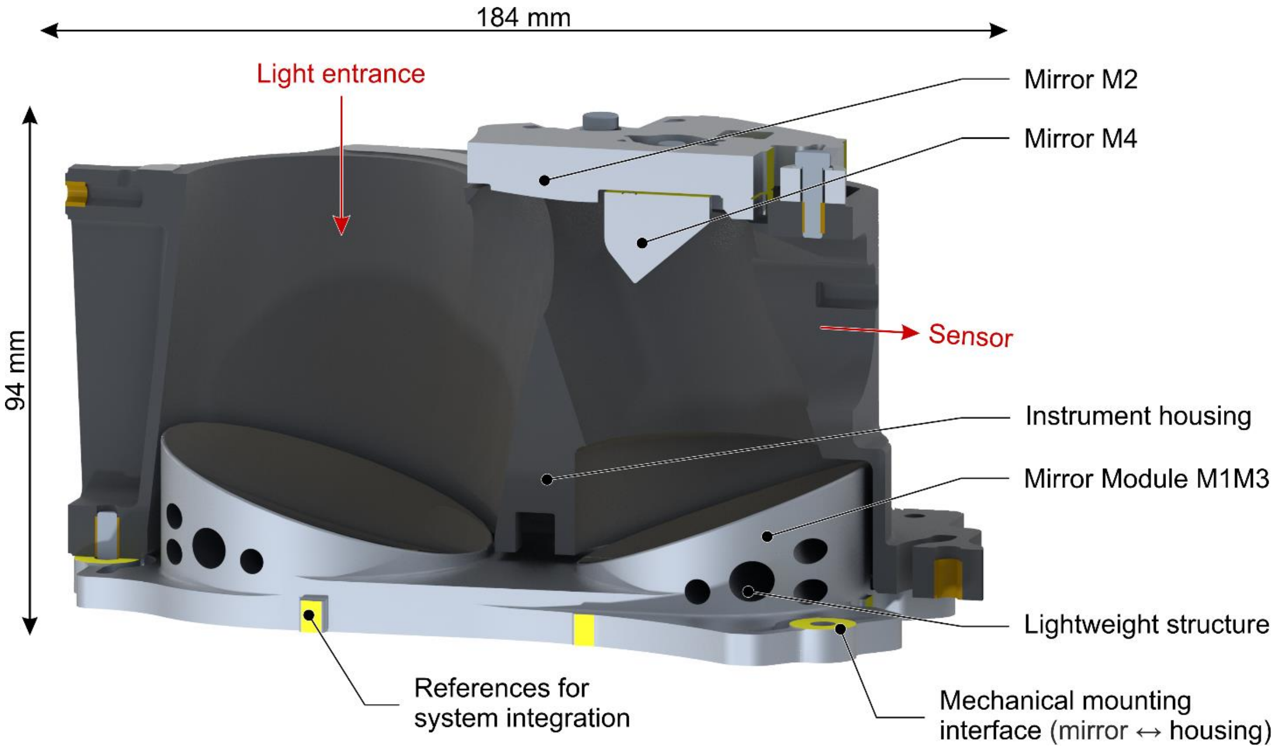

Figure 4. Left: Cut view of the mechanical design of the instrument; Right: Mirror assembly M2 and M4 on the integration fixture

3.1 Optical design

The whole system must fit in approximately 1 U (100 x 100 x 100 mm), with the design goal to maximize the aperture. In this case, a Three-Mirror-Anastigmat (TMA) design was selected, which follows the Korsch design strategy (Figure 5).

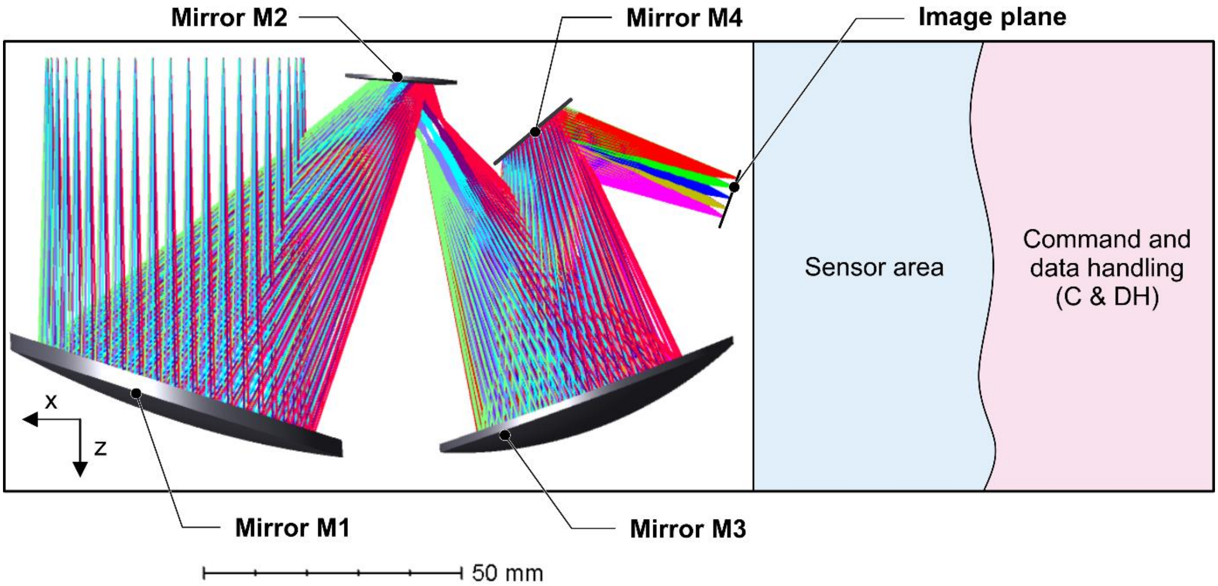

Figure 5. Optical design of the telescope and general structure of the whole instrument (not in scale)

In general, TMA designs are beneficial for applications in small satellites because of their avoidance of aperture obscuration, large Field-of-View (FOV) in relation to their size and an accessible exit pupil for the placement of cold stops (here particularly advantageous because of the application in the infrared spectrum). In contrast to other design strategies, re-imaging TMAs enable use of a field stop very close to the intermediate image (design is relatively insensitive to false light paths as compared to other approaches), and they are able to cover a larger aperture as compared to non-imaging TMAs. [19]

The TMA mirrors are all standard aspheres, aligned on a single optical axis, i.e. all optical surfaces are described in relation to a single optical coordinate system. As a result, the data flow throughout the process chain is simplified. The mirror distribution is positive - negative - positive following a classical TMA design approach, which also means entrance and exit pupils on the same side. Here it was necessary to add an additional folding mirror (M4) to integrate the sensor. The telescope has a focal length of 150 mm, an aperture of F/3.0 and is determined by the required ground resolution at an orbit height of 400 km (ISS). The theoretical performance is close to diffraction-limited, which leaves a margin for fabrication and integration tolerances.

Table 1. Geometry and size of the optical design

Mirror	Geometry	Curvature	Radius	Conic	Outer diameter
M1	asphere	concave	-151,82	-0,805	170 mm
M2	asphere	convex	-58,06	-22,954	36 mm
M3	asphere	concave	-76,53	-0,158	82 mm
M4	flat	0	∞	-	17 mm

3.2 Mechanical design and fabrication of the mirrors

The general system concept and design realization is illustrated in Figure 4. The mechanical design of the mirrors M1 und M3 relies on the duolith-technology developed by Fraunhofer IOF [7]. To enable the manufacturing of two optical surfaces on a common mirror substrate, the optical surfaces are consolidated and treated as a single surface. By this process the two standard aspheres (see Table 1) become one single freeform optical surface and consequently freeform manufacturing technologies must be applied. The schematic principle is shown in Figure 6. Subsequently the local coordinate system for the part (also known as working coordinate system (WCS)) has to be determined. The orientation and positioning of the mirror are determined by several factors, such as the deviation from the best fit sphere, achievable manufacturing parameters, or constraints imposed by the system environment (e. g. in this example, the mirror backplate needs to be parallel to the reference plane of the instrument). [20, 21]

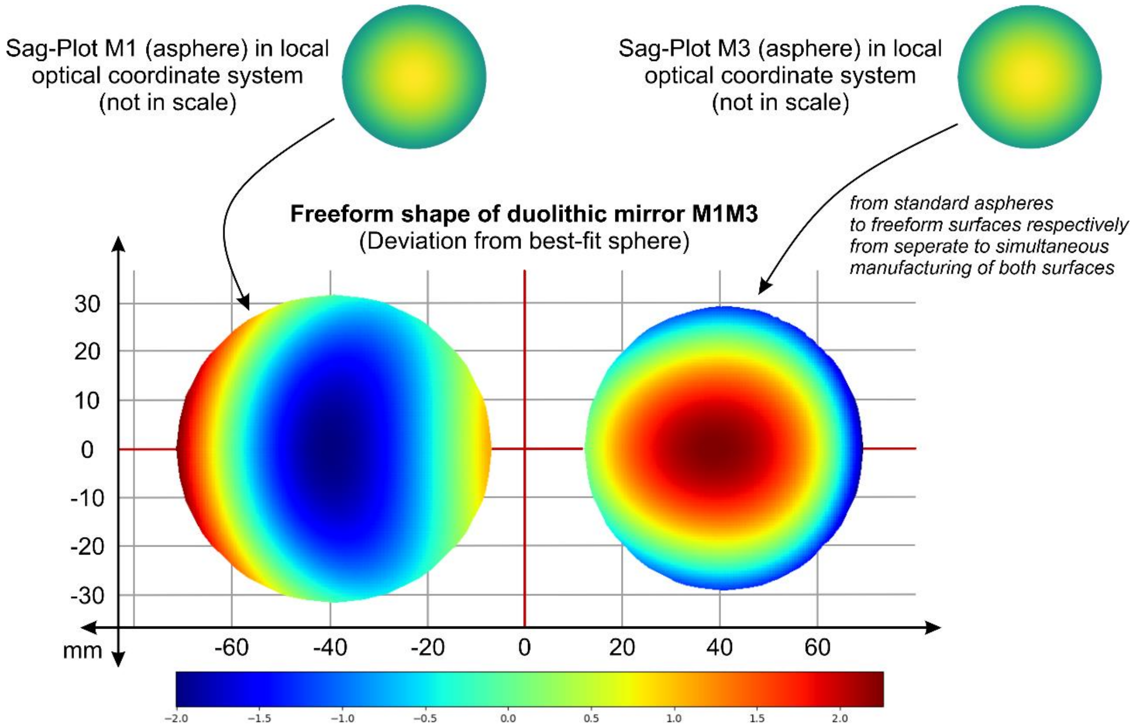

Figure 6. Illustration of combining two aspheres to one freeform surface

In general, a surface has four types of apertures, which are distinguished during the manufacturing process, namely the mechanical as well as the optical machining diameter, outer diameter, full aperture and clear aperture (Figure 7). The full aperture (FA) represents the fully manufactured optical surface and the clear aperture (CA) is the part of the optical surface, which must be fully in line with optical specification. The differentiation between FA and CA is intended to avoid the appearance of edge effects during DT or polishing, which could negatively affect image quality. The machining diameter is relevant for the DT process and symbolizes the imaginary diameter resulting from the rotation around the spindle axis. The outer diameter represents the mechanical boundary of the part. For standard mirrors, which are manufactured on-axis (optical coordinate system and spindle axis are congruent), the machining diameter and the outer diameter are identical. For off-axis- and duolithic mirrors they are different. This fact is important to the design of the mirror. The mechanical mounting interfaces are ideally located in the same mechanical machining corridor for an easier, respectively faster, manufacturing process. It is also crucial that the mechanical machining corridor does not collide with the optical machining diameter, especially if they are at different z-heights. This represents another of the difficulties in designing the mirror module M1M3: the same functional density must be integrated into a smaller space.

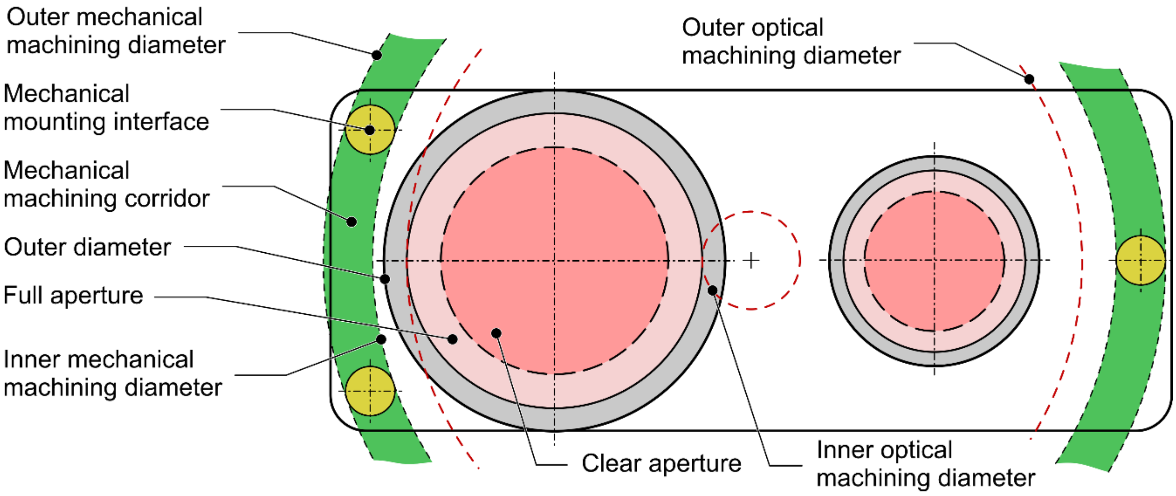

Figure 7. Types of apertures distinguish during manufacturing process (schematically)

The raw body of the mirror substrates for this instrument were manufactured with conventional CNC-milling, while the optical surfaces and mechanical references were manufactured in the same DT process. Through the use of duolithic technology, positioning errors between optical surfaces are reduced, and alignment movements are coupled. This strategy allows for a significantly simplified adjustment of the optical system [22, 23].

As a result of the capable and mastered DT-process, the form and roughness of the mirrors were substantially within specification for application. The required spectral range is in the infrared, so it is not necessary to post-process the surfaces. This results in the advantage, that no plating is needed, which may lead to a CTE mismatch between the plating and the mirror substrate. As a positive consequence, there is no occurrence of bimetallic bending effects, which would limit the usable temperature range. After manufacturing, the mirrors are passivated, then again DT machined and cleaned. Afterwards a gold layer is used as optical HR-coating for all mirrors.

All mirrors are designed with a closed base area (back side), which generally results in a higher stiffness. Moreover, this design also has another advantage when it comes to manufacturing. When a mirror has an open back, the lightweight back structure appears on the optical surface during diamond turning. If the mirror has a closed back, this problem does not occur. Light weighting of the common mirror substrate M1M3 is achieved by drilling holes through the substrate. The thickness of the mirror modules depends on the mechanical and thermal stability as well as the self-weight deformation. The mirrors M2 and M4 remain solid due to the fact that a design as lightweight mirrors does not achieve significant improvements in the weight-to-manufacturing effort ratio.

In general, the steeper the angle between two separate mirror surfaces, the larger is the resulting deviation from the base description (e. g. best fit sphere) of the common surface. As seen in Figure 5, the base angle between the surfaces M2 and M4 is very steep. As a consequence, the parameters required to manufacture the surface exceed the available capabilities, e. g. in needed accelerations or axis travels. Consequently, it was necessary to develop an alternative constructive realization for the mirrors M2 and M4 in order to achieve a duolithic mirror module. Also considered was the use of two separate mirrors that are assembled separately on the instrument housing, but this would result in a more complicated and time-consuming alignment process. It was decided to integrate the mirror M4 onto the mirror module M2. The general integration concept and the manufacturing method make this possible. The critical functional angles (relative position between the global optical axis and local optical coordinate system of M4) are determined through the manufacturing process. The basic concept behind the mirror module M2-M4 and other special features in the design are discussed in chapter 3.4.

3.3 Mechanical design of the instrument housing

The raw body of the instrument housing was manufactured using normal CNC milling processes. To avoid thermally induced deformations, the housing of the component was manufactured from the same material as the mirror modules (EN AW-6061), which results in an athermal behavior of the complete system [24].

Similar to the mirrors, the housing also carries several references, which have an offset to the surrounding structure and are machined by DT. They will be used to define an initial point for the adjustment of the mirrors. Comparatively to other mid- and large-sized instruments, all references can be manufactured within one monolithic housing, simplifying its manufacturing and integration process. The integration concept is described in more detail in chapter 3.4.

The design goal was to enable maximum stiffness of the whole telescope under static and dynamic loads, while reducing the weight. This has been achieved by adding several lightweight structures to the housing. These structures enable an additional reduction in the weight of the instrument without compromising the stiffness of the system. Due to the basic shape of the instrument housing a rectangular structure was applied. The final system weighs approximately 1,16 kg, including the peripheral components, such as bolts and shims. The inner contours of the housing wrap around the optical path to suppress false light. As a further step in improving thermal properties, a black anodized layer was applied. This results in significantly improved radiation characteristics compared to the purely passivated housing.

3.4 Integration and mounting concept

A classical mounting is required to secure the position of the mirror under changing environmental conditions. As a general rule, when designing an optical component mounting, care should be taken to ensure that the wavefront is not affected by the mounting. In addition, it should be ensured that the wavefront aberrations do not exceed the permitted level [25]. This is possible if the mounting does not introduce additional mechanical stress or if thermal loads are adequately compensated. This can be achieved by a statically determined mounting. The state of the art is the use of an isostatic layout, which means that three points at a 120° angle are used to connect the mirrors to the housing as well as the housing to the next higher system level. The mounting is in the best case semi-kinematic, which in principle means that the stiffness of the degrees of freedom (DOF) are independently controlled. As seen in Figure 8, this classical approach could not be implemented completely, due to limited space and the design goal of maximizing the aperture. The figure shows the ideal concept of an isostatic layout of a semi-kinematic mounting (green lines) and the real case how it`s implemented (black lines). The flexible and stiff degrees of freedom can also be seen. In general, the mirror should be stiffer than the decoupling structure to the telescope housing, otherwise the occurring forces will deform the mirror surface [8]. The action line of the decoupling structure has to minimally intersect at a common point, which is called the fix point. In best case the fix point is equal to the center of gravity (COG) of the mirror and therefore allows lateral movement of the mirror module in the reference plane. All other translational DOFs should be stiff. The rotational DOFs have to compensate for unevennesses between the mounting interfaces. The position of the COG is particularly important for the mechanical load cases and determines the resulting forces on the joint. On the one hand, the 120° arrangement causes a uniform distribution of the resulting stresses. On the other hand, the eigenfrequencies decrease. Accordingly, the design process consists of an iterative process to determine the most appropriate design for the application and boundary conditions at hand.

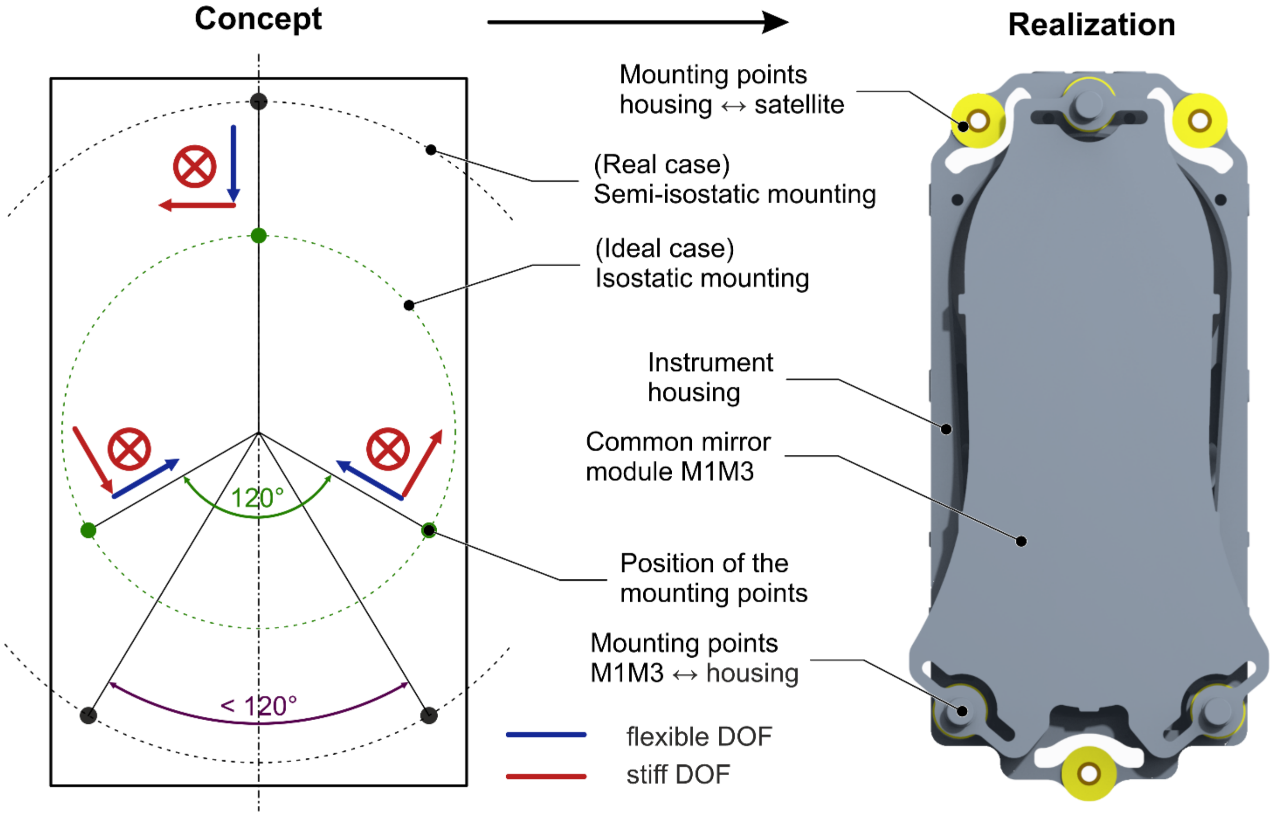

Figure 8. Integration concept of mirror module M1M3 and instrument housing

Compared to the isostatic layout, the action line angles are more acute, resulting in increased mechanical stresses on the decoupling structure in the same environmental conditions. As a result, the permitted mechanical and thermal loads have to be reduced or the decoupling must be stiffer. The selected angle is a compromise between the available space, the required stiffness, and the material limits.

Very important for the design of the decoupling structures between the mirrors and the housing as well as the housing and the next higher system level is that only mechanical forces, which can also be induced by thermal changes, are compensated. The decoupling structures were not allowed to have a thermal decoupling effect in order to minimize temperature gradients in the system. Because of the described athermal system design and the reduced temperature gradients, the optical performance is less sensitive to temperature variations. Consequently, there is no need for a complex thermal management system. The solid-state joints were designed by using an iterative FEA process.

3.5 Alignment concept

The alignment process is one of the major cost and time factors for classical reflective optical systems. This chapter shows that the applied alignment concept effectively reduces time and costs, so that metallic mirror systems also become attractive for the small satellite market. An optical system out of n_i surfaces has $\sum n_i \cdot k_i$ functional relevant DOFs. In the presented system there are 18 of them that must be aligned (according to Table 2: three aspherical surfaces with 5 DOF each and one flat mirror with 3 DOF). The sensor is not considered here.

Table 2. Degrees of freedom (DOF) that must be aligned depending on the base geometry of the optical surface [21]

	Translation	Rotation	Sum k_i
Flat mirror	Z	X, Y	3
Spherical mirror	X, Y, Z	(X, Y)	3 (5)
Aspherical mirror	X, Y, Z	X, Y	5
Freeform mirror	X, Y, Z	X, Y, Z	6

As already described, the mirrors M1 and M3 are combined on a common mirror substrate. Through this step the alignment DOF reduces from 10 to 6, respectively on system level from 18 to 14. Although the rotational and translational DOF of the aspheres are reduced, the combined surface must be treated as freeform and therefore the rotation around z-axes comes into account. The same thing happens through the design of the combined mirror module M2M4. In sum there are 15 DOFs, which are relevant for optical performance and therefore must be aligned.

For mounting and alignment the snap-together approach is utilized to further reduce the necessary alignment DOFs. That means, that functionally relevant DOFs were coupled by manufacturing and so the adjustment accuracy corresponds to the machine and measurement accuracy. In this case, they are distributed as follows in Table 3.

Table 3. Degrees of freedom (DOF) that must be aligned in LisR telescope

Coupled through manufacturing	TZ_{M1M3}, TZ_{M2}, TZ_{M4} RX_{M1M3}, RY_{M1M3}, RX_{M2}, RY_{M2}, RX_{M4}, RY_{M4}	9
Additional alignment required	TX_{M1M3}, TX_{M2}, TY_{M1M3}, TY_{M2} RZ_{M1M3}, $RZ_{M2,}$ RZ_{M4}	7
Separate (not relevant for function)	TX_{M4}, TY_{M4}	(2)
	Sum:	15 (18)

The concept also offers the advantage of binding several rotational DOF through manufacturing Especially for mirrors, the tilting tolerances are critical, so this advantage is more significant than for refractive systems. However, due to the design of the coupling points between the instrument housing and the mirrors, not all freedoms of movement can be restricted by manufacturing precision alone. In conclusion, there are 7 relevant DOFs that have to be manually aligned to ensure the optical function. The separated DOF TX_{M4} and TY_{M4} have no negative influence on the optical performance. As a result of the larger optical surface, the mirror does not produce any vignetting, when it is decentered.

Because of the alignment concept several DOF are adjusted simultaneously ($TX_{M1M3} + TY_{M1M3} + RZ_{M1M3}$, $TX_{M2} + TY_{M2} + RZ_{M2}$ and $RZ_{M4} + TX_{M4} + TY_{M4}$), which follows in a further simplified alignment process. In summary, three manual adjustments are necessary.

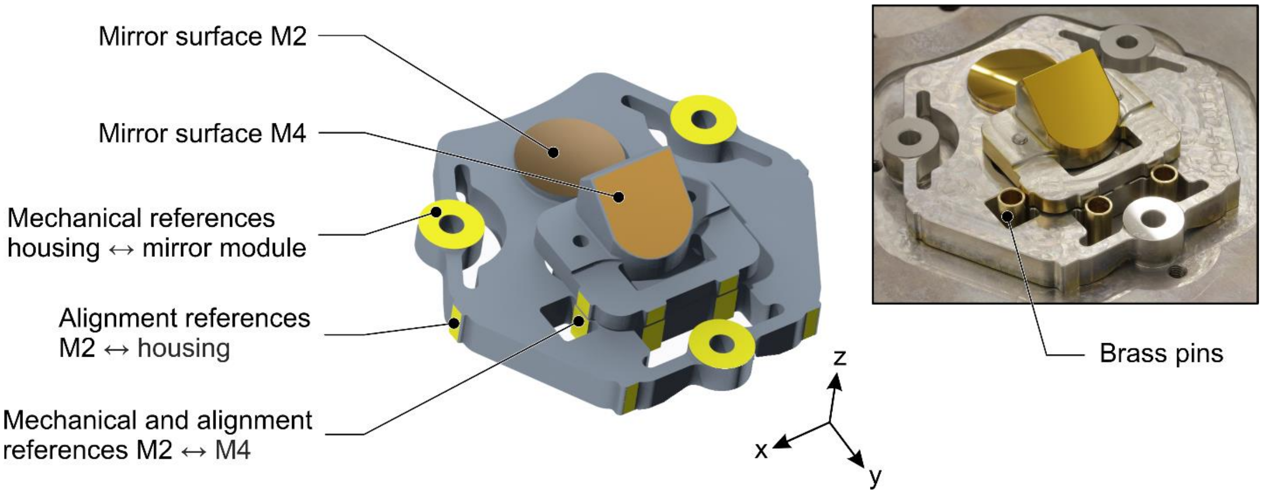

Figure 9. Mirror module M2-M4 with mechanical and alignment references

The alignment of the mirror M4 to the mirror M2 is made via a separate fixture with three brass pins. Through three attachment points and precise manufactured alignment references $RZ_{M4} + TX_{M4} + TY_{M4}$ can be adjusted.

The adjustment of the mirror modules M1M3 und M2M4 is performed without the use of additional external reference marks. The starting points of the mirrors are defined by mechanical stops on several references distributed over the instrument housing. The actual position can be changed by gauging blocks between the components and the respective stops. The fine adjustment steps will be done under continuous interferometric control. The measurements are done in double-pass configuration using a reference surface at the respective image plane [9].

On the one hand, due to the monolithic binding of both mirror surfaces, the DOF are reduced significantly. On the other hand, there are increasing requirements in terms of production and precision of manufacturing. Nevertheless, the integration duration can be significantly reduced from days to hours, which leads to reduction of overall costs, which is a massive advantage for the New Space- and mass market. In particular, this advantage comes into account when large numbers of systems are to be built.

4 SUMMARY AND OUTLOOK

The current paper described the opto-mechanical design system of a small class all-metal telescope in the infrared spectrum for the LisR demonstrator mission on the ISS. After the successful in-orbit demonstration, a further development of the telescope towards a constellation-capable instrument for small satellites is envisaged. Nevertheless, the proposed system demonstrated the compatibility of the classic manufacturing chain known from mid- to large size optical systems for small class optical systems. The paper shows that a high performance freeform metallic mirror system could be manufactured price efficient, but still at high performance. The instrument was successfully launched in February 2022 and is already providing reliable, high-resolution data.

In the future, Fraunhofer IOF will continue its research on the possibilities of metallic optics for the New Space market, e. g. on further improvement of integration concepts, lightweight mirrors and general instrument design through additive manufacturing as well as multifunctional optics for various applications.

5 ACKNOWLEDGEMENT

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