Development of a Freeform Telescope for a Compact and Highly Performing Hyperspectral Imager

Michael Deiml (1), Alessandro Boni (1), Paolo Sandri (1), Thomas Sedlmaier (1), Maximilian Freudling (1), Markus Erhard(1), Matthias Beier(2), Marcel Hornaff(2), Johannes Hartung(3), Ana Baselga Mateo(4)

(1) OHB System AG, Manfred-Fuchs-Straße 1, 82234 Weßling, Germany, +49 (0)8153 4002-0
(2) SPACEOPTIX Gmbh, Hans-Knöll-Str. 6, 07745 Jena, Germany, +49 (0)3641 5540067
(3) Fraunhofer IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany, +49 (0)3641 807-0
(4) ESA ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands, +31 (0)71 565 8792

Abstract

Optical systems based on freeform mirrors have become important in space applications where high performance in small volume is required to tackle mission costs, while reaching high performance required by modern missions. State-of-the-art manufacturing technologies like diamond turning together with surface form correction through magneto-rheological finishing, allow to tackle assembly and alignment challenges that are a result of the lack of any plane of symmetry from freeform optical systems.

Within a GSTP activity funded by ESA, OHB together with SPACEOPTIX and Fraunhofer IOF developed the telescope design for a compact hyperspectral imager with the goal to leverage the unique advantages of freeform surfaces to be employed on a small satellite platform. The optical system is based on a Three-Mirror Anastigmat (TMA) design. The additional reduction of alignment degrees of freedom by manufacturing the first and third mirror on the same substrate further fosters a so-called “snap-in” integration with only minimal alignment activities. The telescope is designed as an all-metal telescope that utilizes a combination of rapidly solidified AlSi40 and a layer of amorphous electroless nickel for the optical components to satisfy the demanding surface form and roughness requirements.

This paper describes the design approach from the system level requirements down to the manufacturing an alignment approach.

1. INTRODUCTION

The demand for higher performance of optical remote sensing instruments usually pushes for larger mirrors when classical design concepts are involved. However, launch costs, mass, and volume restrictions limit the available form factor for satellite instruments, especially when considering the development of satellite constellations. Thus, classical optical systems with spherical or conic surfaces are not always adequate to satisfy the more demanding requirements for instruments in the market of small satellites.

Freeform optics have the advantage that fewer optical elements are required for the control of optical aberrations. This has a significant impact on the size and mass of optical systems. It can also allow reduction of system complexity, simplifying integration and testing, thereby employing freeform optics in all optical systems, ranging from large-scale instruments to low-cost commercial applications. For optical surfaces, it is useful to specify freeform surfaces as a sphere or conic section with additional terms describing the deviation therefrom. These terms can be represented by xypolynomials/ orthogonal Q-polynomials [1], Zernike polynomials [2], Non-Uniform Rational B-Splines (NURBS) [3], Radial Basis Functions (RBF) [4], or any other convenient functional form. Depending on the representation, the freeform terms can have a local or global influence on a surface. Freeform designs can increase the performance of optical systems by a few factors up to a magnitude compared to their classical counterparts [5],[6]. Challenges in the manufacturing of freeform surfaces can be addressed by employing manufacturing tailored design solutions [7]. Research in the fields of metrology, manufacturing, and assembly/ testing of freeforms is progressing together with freeform design [8]. Freeform surfaces are usually manufactured with diamond turning and sometimes polished with magnetorheological finishing or ion-beam figuring. Their surface forms are then verified with computer generated holograms (CGH), stitching interferometers, or profilometers.

Combining all these technologies and tools allows nowadays to produce cutting edge optical systems, for example the demonstrator telescope for the PREMIER mission [9]. In this optical system, three freeform mirrors are “snapped” into their mechanical housing with minimal effort for alignment, reducing considerably costs and time for assembly of the telescope. The SpectroLite instrument [10] is another example of a freeform optical system. The freeform elements are embedded into a spectrometer that allows to monitor Earth in the visible range with high spectral resolution and good imaging performance. The structure onto which the mirrors are mounted is 3D-printed. The HyperScout instrument [11] with a volume of one liter includes four mirrors and provides a large field of view at moderate optical performance. This instrument demonstrated the advantages of freeform optics for miniaturization of an instrument. In line with these instruments, this paper describes the development of the Compact Hyperspectral Imager (CHI) from system level requirements to manufacturing and alignment concept. In the first sections we describe the application scenario with its system requirements. We then present the optical and mechanical design, showing the main characteristics and we describe its performance. We conclude then with a description of the manufacturing and integration approach giving some insights on the following activity.

2. THE COMPACT HYPERSPECTRAL IMAGER

2.1. Applications and Observation Scenario

The idea behind the instrument concept is to build a small hyperspectral instrument that partially fulfills parts of the CHIME instrument requirements. CHIME stands for the Copernicus Hyperspectral Imaging Mission for the Environment of ESA that is currently under development and will be one of the new remote satellite systems in the Copernicus program. Such an Earth observation satellite will support the generation of new data products in the area of agriculture, food security, raw materials, soils, biodiversity, environmental hazards, inland and coastal waters, and forestry. This broad range of applications is achieved by continuous spectral sampling of a large wavelength range from the visible towards the near infrared with a high Signal-to-Noise Ratio (SNR). The distinguishing factors to CHIME are the size of the instrument and the stringent use of cutting-edge technologies such as freeform optical elements bordering the technologically feasible. While the use of freeform systems can partially compensate for performance degradation, not all performance metrics of CHIME can be fulfilled. Specifically, the SNR and the swath width are not up to the performance of CHIME. Nevertheless, through a sophisticated operational concept, the SNR can be recovered for regions of interests by targeting these regions through spacecraft tilting. The swath width can be increased to even exceed CHIME by using multiple instruments, either on the same satellite or on a constellation of satellites.

The Compact Hyperspectral Imager (CHI) is based on a slit spectrometer with a telescope to image the Earth´s surface onto the slit for push-broom spectral scanning. The instrument is designed for an

Earth observation altitude of 680 km in the wavelength range from 0.4 µm to 2.5 µm with a spectral resolution of 10 nm, a GSD of 26 m, and a swath width of 77 km.

The instrument shall fit within the OHB LuxSpace Triton-X platform. An envelope of 440x440x250 mm^3 is reserved to the telescope with a mass requirement of less than 20 kg

Due to the envelope of the instrument, the entrance aperture becomes relatively small which reduces the SNR. However, the SNR can be increased by viewing a scene from different directions to effectively increase the integration time.

2.2. Instrument Concept and Design Parameters

This GSTP activity focuses onto the freeform telescope for imaging Earth onto a slit. In addition, to broaden the use-case of the telescope, it was also be optimized for the along track direction, perpendicular to the slit, to be able to also use it with a gradient filter on the detector or with a detector for standard imaging applications, besides its nominal use case as the telescope for a grating spectrometer, see Figure 2-1.

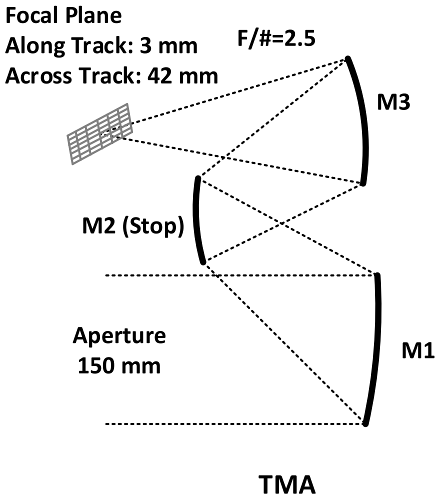


Figure 2-1: Concept of the telescope with 2D matrix sensor

To utilize freeform optics and to reduce its size, the telescope will be designed as fairly fast optical systems (low F-Number).

The key parameters for this design are described in Table 2-1. The baseline is the use of a Chroma-D detector from Teledyne with 18 µm pixel pitch and 3000 x 512 pixels. The telescope becomes fairly fast with an F-number of 2.5 and an aperture of 150 mm diameter.

Table 2-1: Key parameters of the Compact Hyperspectral Imager.

Orbit Altitude [km]	***680***
Wavelength Range [µm]	***0.4 – 2.5***
Entrance Aperture Diameter [mm]	***150***
Telescope F-number [-]	***2.5***
Focal Length [mm]	***371***
Full Field of View Across Track [deg]	***6.48***
Full Field of View Across Track [deg]	***0.43***
Swath Width [km]	***77.0***

Ground Sampling Distance [m]	***26***
Pixel Number Across Track	***3000***
Slit Width [µm]	***14***
Pixel Pitch [µm]	***18***

Given the GSD and swath characteristics mentioned above two of these instruments need to be mounted next to each other to fulfil the coverage requirement of CHIME or EnMAP. Nevertheless due to its compactness, it is possible to use one instrument on a small satellite. Coverage and revisit time requirements can then be fulfilled with a constellation.

Based on the key design parameters above, an SNR analysis was conducted to determine whether the instrument can achieve similar SNR as CHIME. Therefore, the land reference spectrum (Lref_L) for the CHIME analysis is used to calculate the SNR. The analysis distinguishes between two integration times for the push-broom operational mode and for the targeting operational mode. The transmission of the optical system is set to 30%, which considers the reflectivity of six optical surfaces and an average grating efficiency of 40%. A background signal of 10000 electrons corresponds to straylight and other background sources that can be corrected for that only their shot noise influences the SNR. The used dark current value considers cooling the Chroma-D detector to a temperature of 175 K. Readout noise and quantification noise are considered for two different gain levels that depend on the overall signal at the detector. Using these information, the SNR is calculated for a few selected wavelengths and compared against the SNR requirement of CHIME. Figure 2-2 summarizes the results. The SNR for push-broom operation is in the range of the SNR requirement, but mostly lower than required. The SNR can be significantly increased by using the targeting mode with only moderately increasing the integration time (4x).

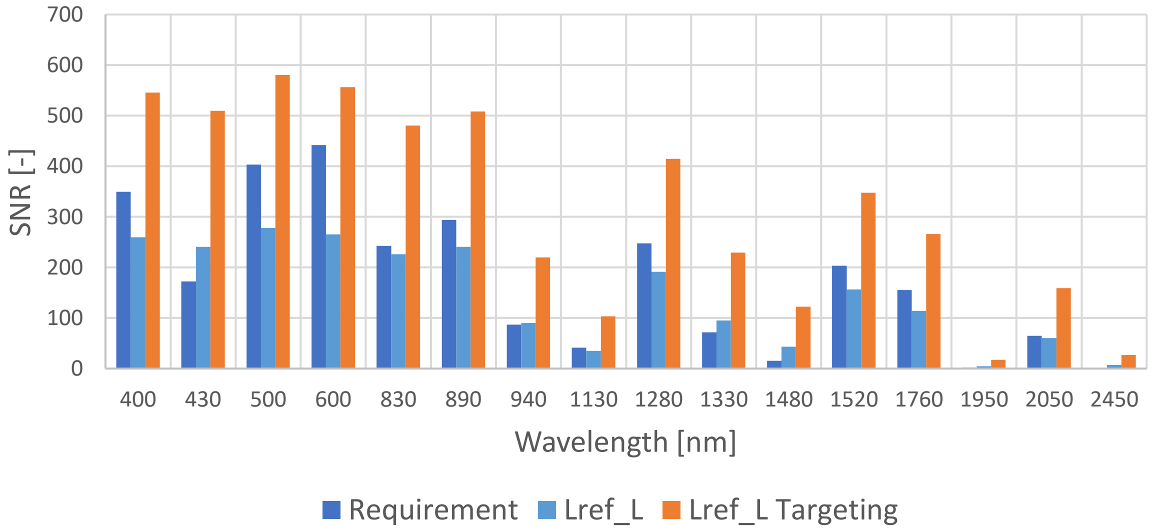


Figure 2-2: SNR for selected representative wavelengths for the reference radiance using push broom mode (Lref_L) and using the targeting mode (Lref_L Targeting). The SNR is compared against the SNR requirement of CHIME.

3. COMPACT HYPERSPECTRAL IMAGER TELESCOPE DESIGN

3.1. Performance Requirements

Within the GSTP activity, the project focused on the development of the telescope for the Compact Hyperspectral Imager. The instrument architecture provides the framework for which the telescope is designed. Table 3-1 summarizes its key design requirements. The focal length and entrance aperture have been repeated from above and extended with tolerances. The performance requirements of the telescope are the MTF at detector Nyquist that influences the effective spatial resolution, the transmission and telecentricity as a proxies for the SNR requirement, and the distortion to limit the geometric aberrations that need to be corrected in post-processing. The material system is RSA443/ AlSi40, rapidly solidified spin-melted aluminium to realise an athermal design and a high quality surface finish without extensive polishing.

Table 3-1: Design requirements for the CHI telescope

Focal Length	***371 +/- 7 mm***
Entrance Aperture	***150 -1/+4 mm***
Slit Size	***42 mm x 14 µm***
MTF @ detector Nyquist freq. (36 lines/mm)	***> 0.6***
Transmission	***> 87%***
Telecentricity	***< 15°, < 5° (goal)***
Distortion	***< 2%***
Material System	***RSA443, AlSi40***

3.2. Optical Design

The telescope consists of three main elements, which are the three freeform mirrors M1, M2, and M3. Mirrors M1 and M3 are manufactured together on the same substrate M1M3, which is one of the key features for the snap-in integration concept. Figure 3-1 shows the overview of the CHI telescope with labels for these major components and the image plane, where the spectrometer slit is located. The aperture stop is at the M2 mirror.

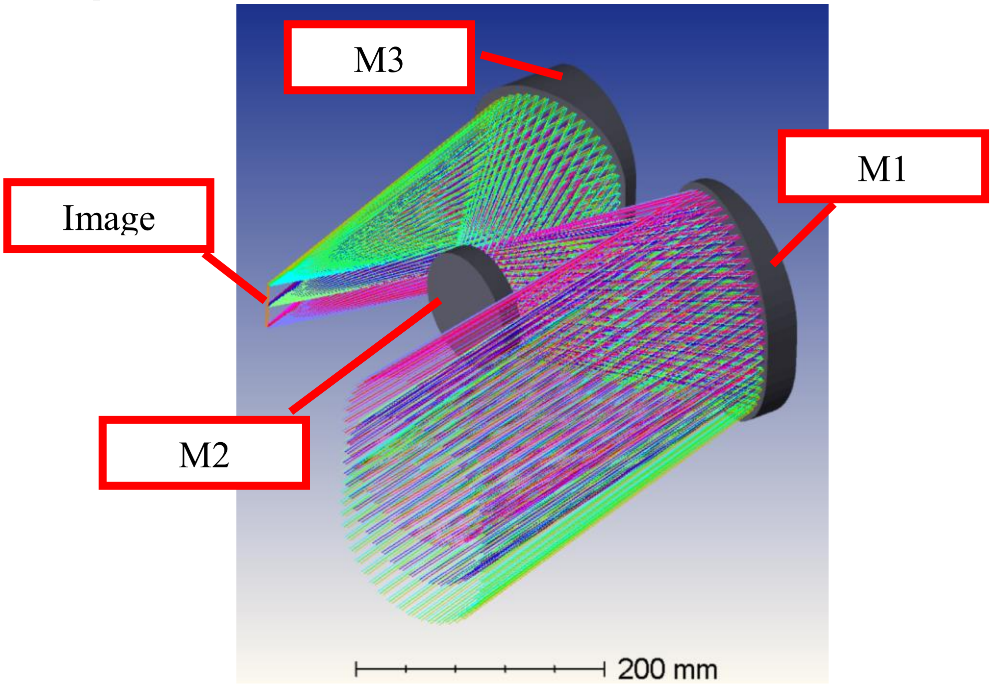


Figure 3-1: Overview of the CHI telescope optical layout showing the location of the slit in the image plane.

The M1M3 mirror is fairly large with a size of about 380 mm in diameter. The rotational axis is defined such that the radial extension is smaller than 225 mm and that the residual sag deviation from a reference asphere is less than 30 mm (Maximum manufacturable sag deviation). Figure 3-2 shows the definition of the complete mirror (together with M3). The aspheric coefficients in the image title describe the underlying asphere which is followed by the slow moving axis of the turning machine. The fast servo tool follows the residual sag shown in the figure that the resulting freeform surfaces are the desired M1 and M3 mirror surface forms. The turning axis lies thereby in the origin of the plot, which means that the M1M3 needs to be mounted off-centred to the turning machine. The M2 mirror is an almost rotationally symmetric mirror with a freeform sag relative to the underlying conic of 3.24 mm, which is also smaller than the required 30 mm, see Figure 3-3. The mirror is the aperture stop of the system, therefore a ring will be mounted on top of the surface to define the aperture

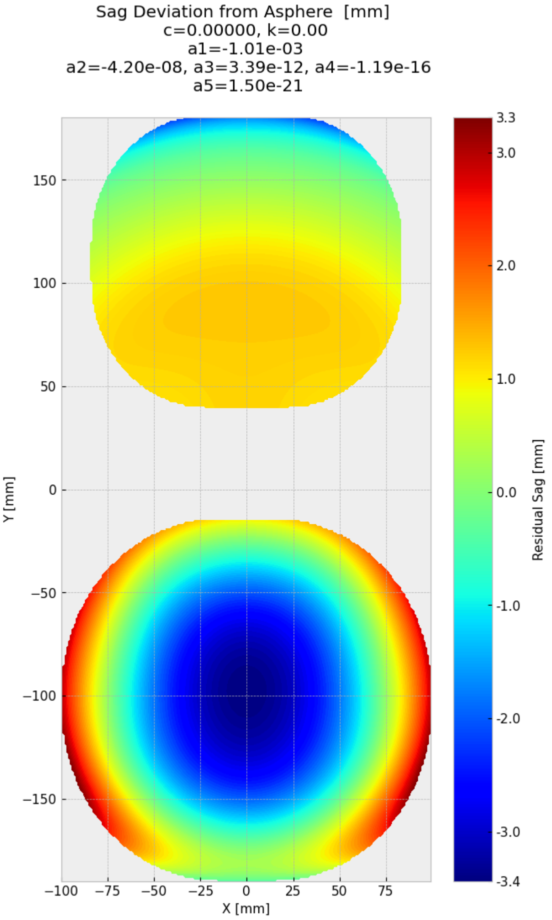


Figure 3-2: Surface sag deviation from reference surface of the M1M3 mirror.

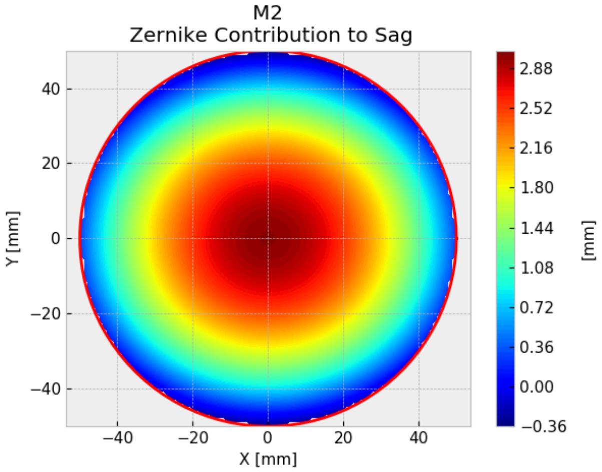


Figure 3-3: Freeform sag contribution for the M2 mirror.

3.3. Mechanical Design

The CHI telescope consists of a housing manufactured in one piece onto which the two mirrors blocks, M1M3 and M2 are assembled. The whole assembly is completed with external and internal baffles, alignment features and three mounting flexures. The given envelope is derived from the Triton-X platform from LuxSpace and set to 440 x 440 x 250 mm^3. Figure 3-4 shows the whole assembly of the telescope.

Both mirrors assemblies have been designed according to optical requirements and manufacturing constraints iterated with the manufacturer. As described before, M1 and M3 mirrors have been designed to be manufactured in one piece together, with proper lightening to reduce the weight of the element. M2 mirror requires the integration of the aperture stop. This is realized by threading the lateral cylindrical surface of the mirror onto which the aperture stop can be screwed. To reduce mounting stresses by manufacturing tolerances flexures are realized with different solutions for each mirror assembly.

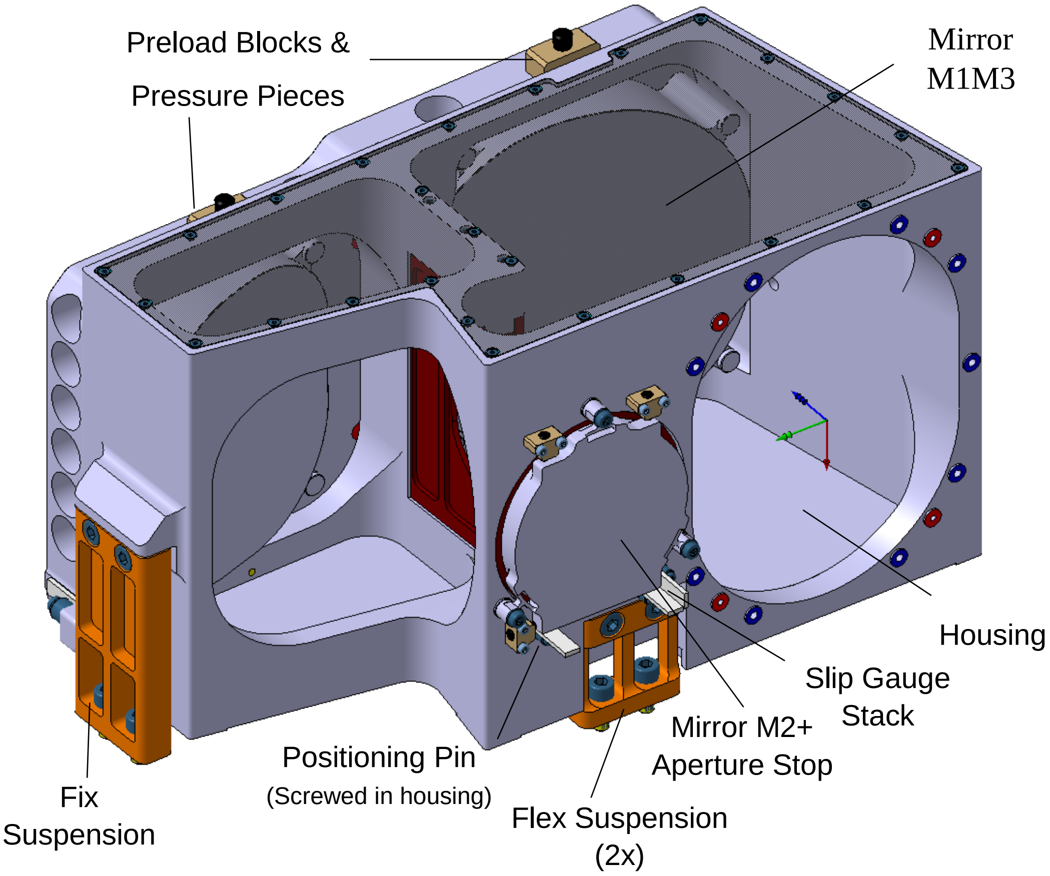


Figure 3-4: Overview of CHI telescope

With what concerns integration, positioning stops are foreseen to be able to have a precise and repeatable positioning of the mirrors in lateral directions. Torsion locks are included to block any potential torsion at the mounting interface during application of the mounting torque. Figure 3-5 and Figure 3-6 show the two assemblies of the mirrors.

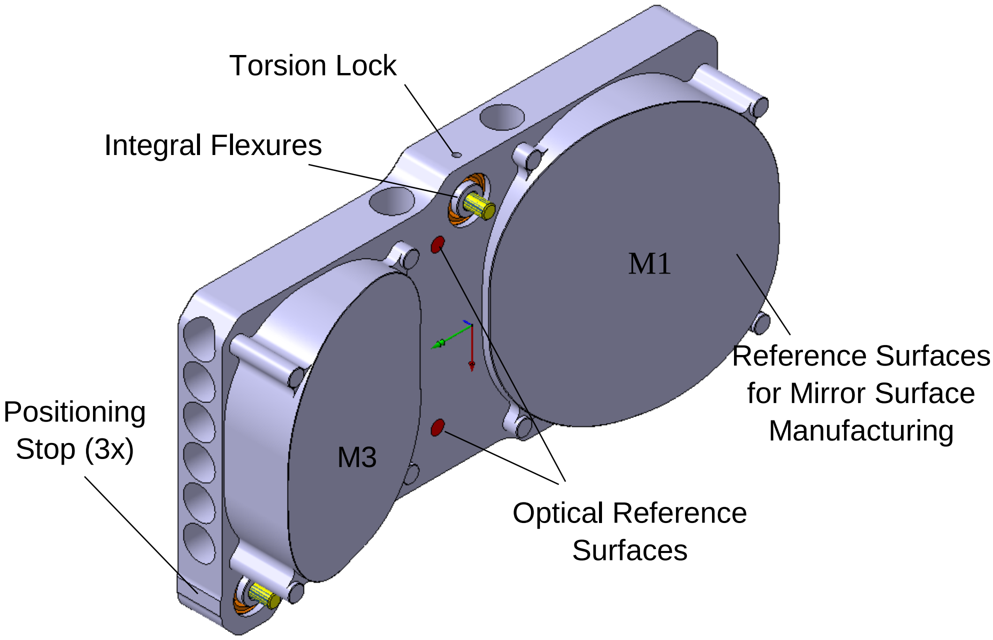


Figure 3-5: M1M3 mirror assembly

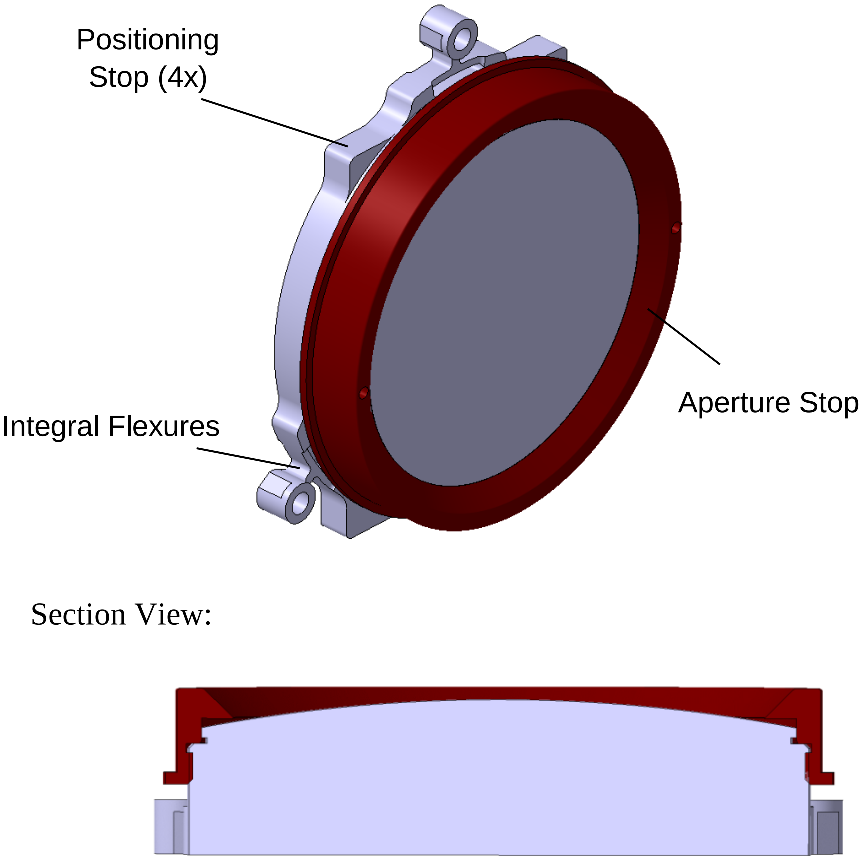


Figure 3-6: M2 mirror assembly

3.4. Optical Performance and Tolerances

The MTF for the Nyquist frequency (36 lines/mm) varies between 0.75 and 0.87, shown in Figure 3-7, with considerable margin to be used for manufacturing and alignment uncertainties.

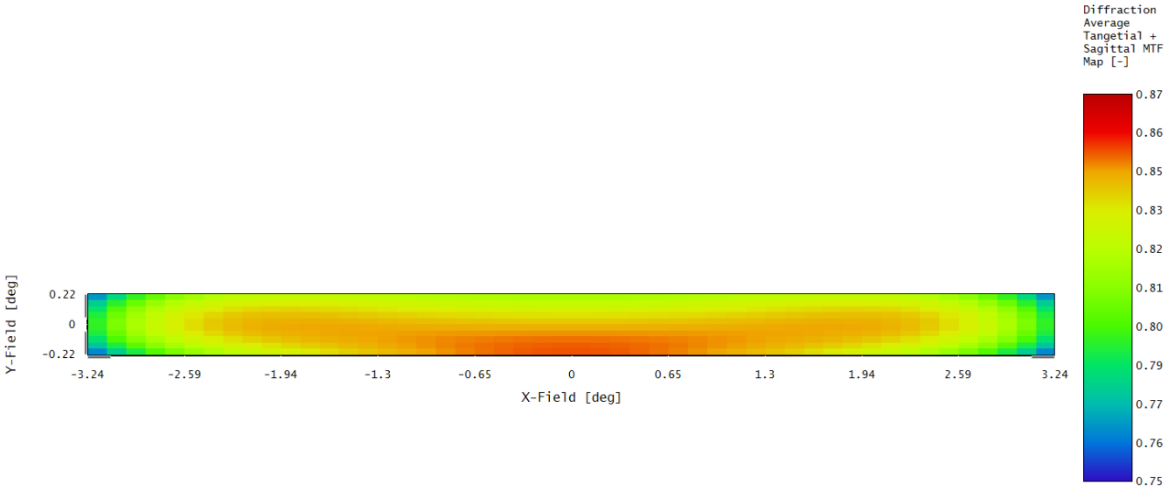


Figure 3-7: Average sagittal and tangential MTF for 36 lines/mm in dependence of field position.

The telescope has a distortion less than 0.8%, which is acceptable considering the requirement of less than 2% distortion. Thereby, the distortion is divided into <162 µm smile and <0.9 µm keystone. Keystone and Smile are defined as in Figure 3-8. Keystone is the change in magnification in along-track direction and smile is the curvature of the scene viewed on the Earth´s surface. Especially the very low keystone of the telescope makes it suitable for multispectral applications. The telecentricity is with < 0.7° and < 12° in the two directions lower than the requirement of 15°, but higher than the goal of 5° in one direction.

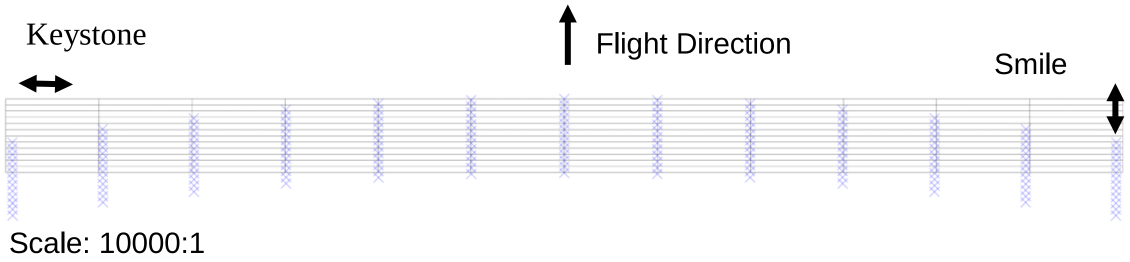


Figure 3-8: Distortion of the CHI telescope.

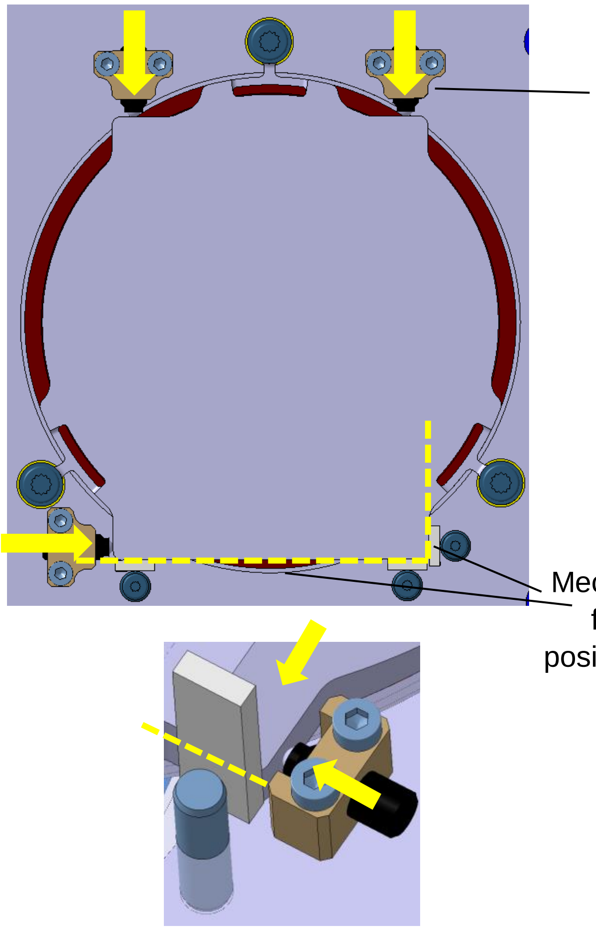
To achieve such a performance practically, tight and challenging tolerances need to be achieved during manufacturing and alignment. These include surface form errors of the mirrors less than 20 nm (RMS) with respect to the optical coordinate systems, positional tolerances of the mirrors with tilts better than ± 5 arcsec and decenters less than ± 5 µm with respect to the optical coordinate system of the mirrors. The housing interfaces need to be also manufactured ultra-precisely with common interface plane uncertainties less than ± 5 arcsec/ ± 5 µm relative to the global coordinate system and common zones on all interfaces (flatness over interfaces) better than ± 5 µm. The developed manufacturing concept and the heritage with similar telescopes allow to suggest that these objectives can be achieved.

4. MANUFACTURING AND ALIGNMENT CONCEPT

Both mirrors are made of Aluminium RSA443/AlSi40 blocks which are then machined by Single Point Diamond Turning (SPDT). This alloy has been chosen for its coefficient of thermal expansion (CTE) close to that one of NiP, used to achieve the desired form error. The material combination reduces thermal induced stresses and improves the athermal behaviour of the telescope. Also the housing follows a SPDT machining process at the interface surfaces in line with the snap-in integration process.

Both mirrors will undergo the same manufacturing process, result of a technological heritage as in . After a first machining on a 5-axis CNC milling machine the main optical mirrors surfaces are generated using a diamond turning machine with highly dynamic fast servo tool. Additionally, mounting interfaces and optical reference surfaces (for CGH metrology) are machined. Mirrors elements are then coated with a 100 µm layer of NiP to first protect them, second to achieve a better surface quality. M2 mirror element slightly differs in the process as the thread for aperture stop integration needs to be masked during this phase. After the NiP coating the diamond turning process is repeated again on optical surfaces, mechanical mounting interfaces and optical reference surfaces. Form error corrections and better surface finish are supported by interferometric and profilometric shape. Next step is a Magnetorheological Finishing (MRF) figure correction, a technique which is used in conjunction with interferometric and profilometric surface shape metrology to iteratively reduce the form error as well as residual marks from SPDT. Roughness is eventually controlled by Computer Controlled Polishing (CCP) smoothing using a CNC polishing machine with soft polishing tools; softness of the tools determines the impact on only surface roughness. After a cleaning process following the machining process a high reflecting protected silver coating is applied to the clear apertures of the mirrors (conveniently masked).

One major aim of this project is to assemble the freeform telescope without any alignment iterations, just based on the measurement results of the positioning pins and the mirrors themselves. Most of the open degrees of freedom are already fixed by the quality of the ultra-precision machining approach for both the mirrors and the housing.



Preload Bloc:
Constant preload
by pressure
pieces

Mechanical Stop:
for nominal
position by pin/slip
gauge

Figure 4-1: Positioning / mounting approach

Nevertheless, to stay flexible, some alignment features are foreseen in case they are needed. The idea is, to use nominal slip gauges for the reference position. If any modification is necessary, the mirrors can be aligned in lateral and clocking position by using different slip gauge stacks. Pressure pieces guarantee a constant and repeatable preload during positioning. Figure 4-1 shows the approach just described.

5. CONCLUSION AND FUTURE ACTIVITIES

This contribution described the conceptual design of a telescope for a remote sensing instrument based on an innovative freeform optical system. It was matured on telescope level within a GSTP activity of ESA that included a manufacturability and risk assessment. The next step is the hardware development of the demonstrator telescope to verify that the high performance and tight tolerances can actually be achieved.

The CHI telescope is currently under manufacturing at SPACEOPTIX GmbH and Fraunhofer IOF. The following pictures show the status of the mirrors and the housing. First measurements indicate already good results in terms of mirrors quality.

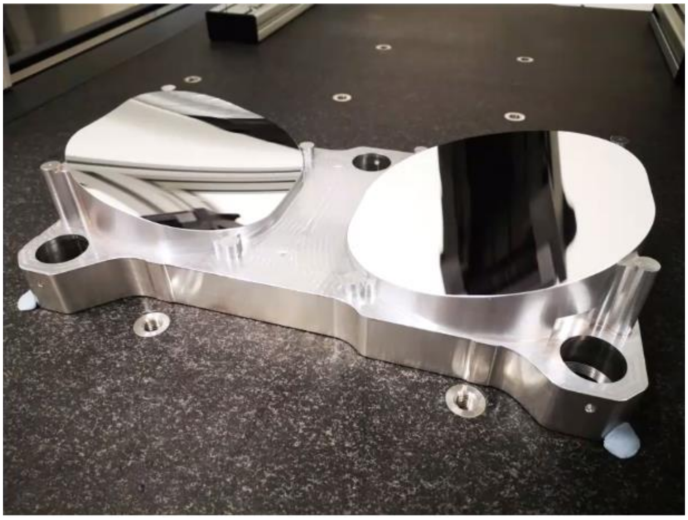


Figure 5-1: M1M3 assembly made of Al6061 after first SPDT.

Figure 5-2: M2 mirror made of Al6061 (left) and AlSi40 (right) after SPDT.

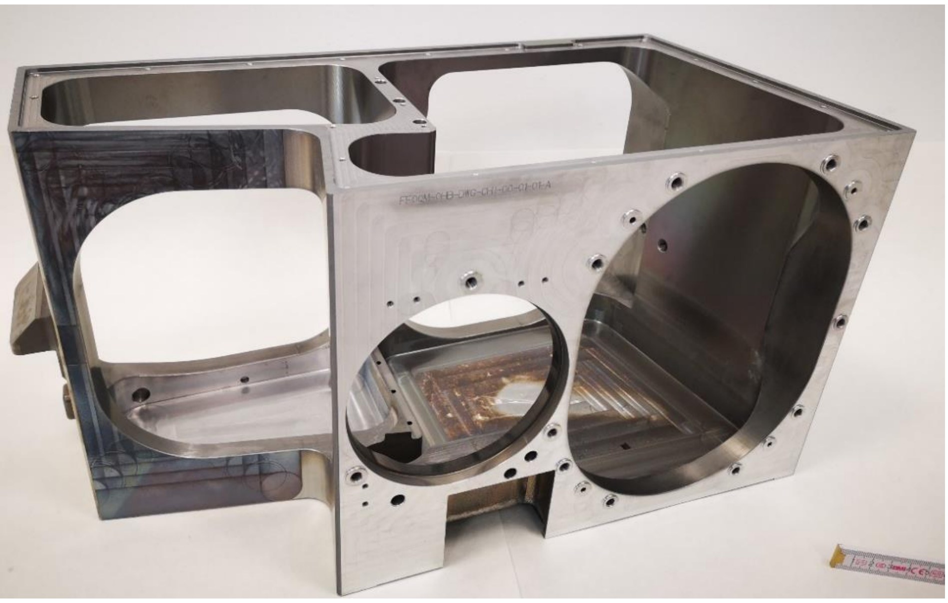


Figure 5-3: AlSi40 Housing after CNC machining.

The next steps are the snap-in integration and the verification of telescope performance. In parallel, the mission concept is further refined to mature also the other aspects of such an instrument that it can be demonstrated in a mission.

6. ACKNOWLEDGEMENT

This de-risk activity was conducted under the ESA GSTP contract 4000127621/19/NL/BJ/zk. We thank Luca Maresi from ESA for his continued support, valuable feedback in reviews, and overall fruitful project work.

7. REFERENCES

[1] Menke, C., Forbes, G. W., *Optical design with orthogonal representations of rotationally symmetric and freeform aspheres*, Adv. Opt. Techn. 2(1) 97-109, 2013.

[2] Fuerschbach, K., Rolland, J. P., Thompson, K. P., *A new family of optical systems employing phi-polynomial surfaces*, Optics Express, 19/22, 2011.

[3] Chrisp, M., Primeau, B., *Imaging with NURBS Freeform Surfaces, Imaging and Applied Optics*, OSA Technical Digest, 2015.

[4] Cakmakci, O., Moore, B., Foroosh, H., Rolland, J. P., *Optimal local shape description for rotationally non-symmetric optical surface design and analysis*, Optics Express, 16/3, 2008.

[5] Duerr, F., Meuret, Y., Thienpont, H., *Potential benefits of free-form optics in on-axis imaging applications with high aspect ratio*, Optics Express, 21/25, 2013.

[6] Garrard, K., Bruegge, T., Hoffman, J., Dow, T., Sohn, A., *Design tools for freeform optics*, Optics and Photonics, San Diego, California, United States, 2005.

[7] Fuerschbach, K., Davis, G. E., Thompson, K. P., Rolland, J. P., *Assembly of a freeform off-axis optical system employing three phi-polynomial Zernike mirrors*, Optics Letters, 39/10, 2014.

[8] Peschel, T., Damm, C., Scheiding, S., Beier, M., Risse, S., Nikolov, S., Holota, W., Weiß, S., Bartsch, P., *Anamorphic telescope for Earth observation in the mid-infrared range*, ICSO 2014, Proc. of SPIE Vol. 10563, 2014.

[9] Peschel, T., Damm, C., Scheiding, S., Beier, M., et al., *Anamorphotic telescope for earth observation in the mid-infrared range*, International Conference on Space Optics — ICSO 2014, Proc. of SPIE Vol. 10563, 105631Y, 2014.

[10] De Goeij, B.T.G., Otter, G.C.J., Leemhuis, A., *SPECTROLITE: Hyperspectral Imager Technology, Instrument Development and TNO Roadmap*, The 4S Symposium, Sorrento, Italy, 2018.

[11] Cosine Measurement Systems, *HyperScout Product Specs*, https://hyperscout.nl/product/, Last access: 22.01.2019, 2016.

[12] Beier M., Hartung J., Peschel T., Damm C., Gebhardt A., Scheiding S., Stumpf D., Zeitner U. D., Risse S.,Eberhardt R., Tünnermann A., *Development, fabrication, and testing of an anamorphic imaging snap-together freeform telescope*, Appl. Opt. 54, 3530-3542 (2015).

[13] Beier M., Risse S., Holota W., Straif C., *Fischer S., Metal Mirror Based VIS Freeform Telescope with Smart Integration Approach*, International Conference on Space Optics, ICSO, Chania (GR), 2018.