International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ICSO 2022
International Conference on Space Optics
3 – 7 October 2022 | Dubrovnik | Croatia

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esa icso proceedings cnes

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127772Y · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690313

Miniature three-mirror telescope for the thermal infrared

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ABSTRACT

The current paper describes the optical and mechanical design of a compact Three-Mirror Anastigmate (TMA) telescope which is installed at the ISS as an earth observation demonstrator for the thermal-infrared spectral range. The TMA bases on a Korsch type[1, 2] design. It has a focal length of 150 mm and an aperture of F/3 and allows for a diffraction limited performance at the design wavelength of 10 µm. The ground resolution reaches 80 m from the ISS. The mechanical design fits into a design space of 80x80x150 mm³ which would correspond to 1.5 U of a typical CubeSat for the telescope or 3U for the whole instrument, respectively.

Keywords: Three-Mirror Anastigmate, all-metal, thermal infrared, CubeSat.

1. INTRODUCTION

Climate change has considerable impact on the supply of water for agriculture. By monitoring the soil moisture from space, water can be used more economically.In this framework the German start-up ConstellR plans to launch multiple micro-satellites which provide respective observations in the thermal infrared in the range of 8…12 µm. ö

A first demonstrator was installed on the Nanoracks' NREP platform of the ISS in February 2022. The optical system of the demonstrator was designed at Fraunhofer IOF in Jena and built by its spin-off SPACEOPTIX on behalf of Fraunhofer EMI and its spin-off ConstellR. The requirements for the telescope are listed in Table 1.

Table 1. Requirements for the telescope.

Parameter	Value
Orbit height	400 km
Ground resolution	80 m
Detector Size	320 x 256 Pixel
Field size	3.67° x 2.93°
Aperture	62 mm … 80 nm
Wavelength range	9.3 µm … 11.3 µm
Available volume	80x80x166 mm³
Maximum mass	1 kg
Pixel Pitch	30 µm

The current paper describes the optical and mechanical design of the telescope: A compact Three-Mirror Anastigmate (TMA) telescope with a focal length of 150 mm and an aperture of F/3 based on a Korsch[1, 2] type design. A fold mirror was added to adapt the telescope to the detector.

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To make the telescope better realizable as an all-metal system and to facilitate an easier alignment process the design was modified so that mirror pairs can be arranged on a common substrate. Both mirrors on a common substrate can be made in a single diamond turning run which guarantees for extremely tight position tolerances between the respective mirrors[3-6]. Furthermore, optical and mechanical reference structures were integrated into the mirror substrates. The approach results in some constraints on the surface shapes of the respective mirrors and on the distances between the mirrors in the telescope. These constraints had to be considered in the optical design.

2. OPTICAL SYSTEM OF THE TELESCOPE

In order to obtain a reasonable optical performance over the whole field of view given in Table 1 a three-mirror telescope design is required. Such so-called Three-Mirror Anastigmates were first investigated by Korsch[1, 2] in the 1970ies. There are two flavors of TMA which differ in the existence of a real intermediate image inside the telescope as well as of an accessible exit pupil. In the case of a thermal-infrared system a real exit pupil will be required to accommodate the cold stop of the detector. Thus, we chose a type II TMA as a starting design. As an additional constraint the preferred manufacturing method[3-6] requires approximately equal distances between the mirrors. Taking into account these constraints as well as the available space we obtained a start design which may be described by the parameters given in Table 2 (using the terminology introduced by Korsch[1])

Table 2. Parameters of the start design for the telescope.

Parameter	Value
Focal length	150 mm
ε	-0.07
m_2	-1.26
m_3	1.58

The start design was transferred to ZEMAX as an obscuration-free off-axis system. The conic surfaces of the start design were replaced by rotationally symmetric polynomial aspheres. The common optical axis of all three mirrors was retained. The whole telescope is still rotationally symmetric, though the mirrors are positioned off-axis.

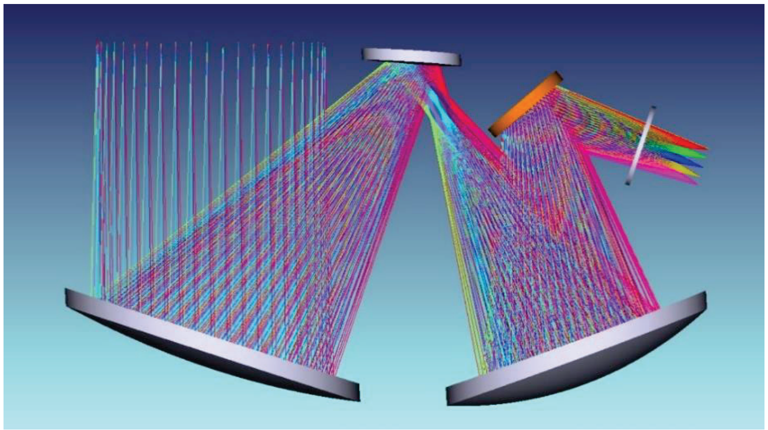

Figure 1. Optical design of the miniature three-mirror telescope. The detector is located on the right side.

The resulting final design is shown in Figure 1. A flat fold mirror has been added to accommodate the detector interface. For straylight suppression a baffle was added in the plane separating the first two mirrors from the rest of the system.

2.1 Performance of the optical system

The performance of the optical system (as designed) is diffraction-limited over the full field of view. At 10 µm the r.m.s. wavefront error reaches λ/16.5 in the very edges of the field and is better than λ/25 over most of the field. The respective results are summarized in Figure 2.

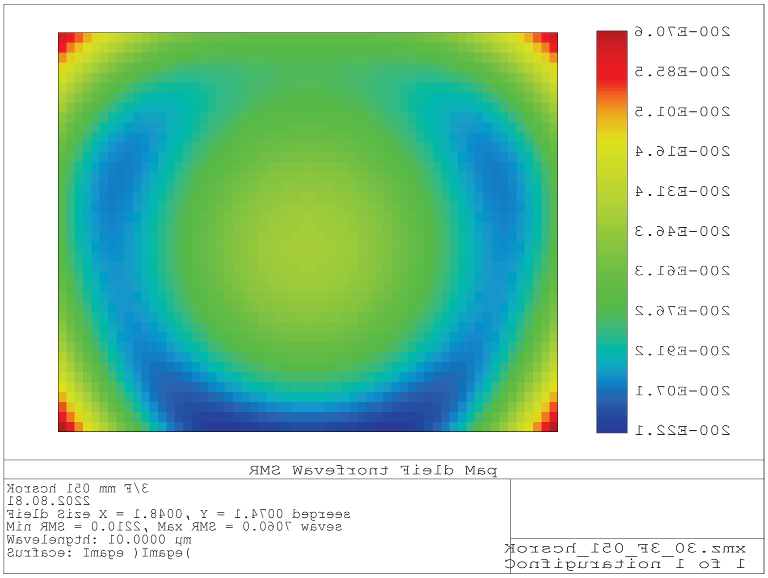

Figure 2. Distribution of the r.m.s. wavefront error of the TMA over the field of view.

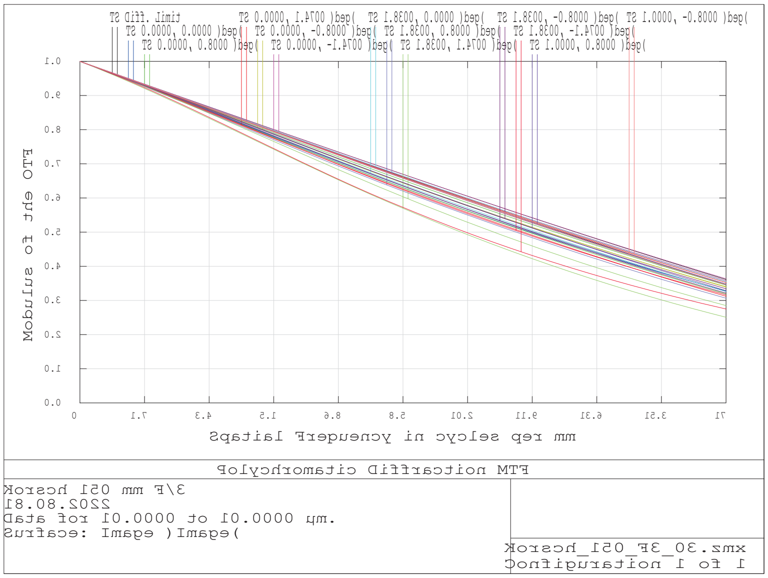

Figure 3. Modulation transfer function of the TMA.

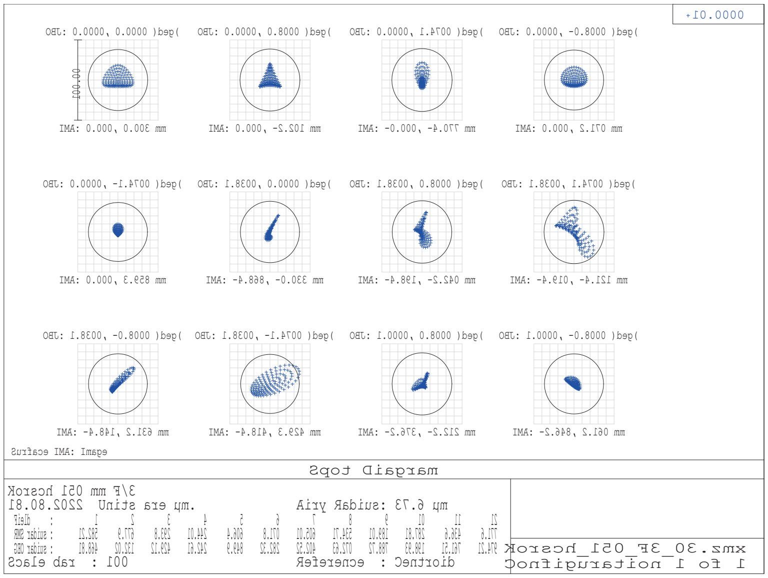

Figure 4. Spot images of the TMA.

Corresponding results for the modulation transfer function and the spot sizes are given in Figure 3 and Figure 4, respectively. Both results also show clear diffraction limitation.

2.2 Tolerancing concept

The mechanical layout of the telescope system relies on IOF's duolith concept[3-6]. The first and third mirrors share a common substrate and are manufactured in the same machining run. Thus, the relative position tolerances of those mirrors may be very small. Furthermore, the design concept allows for a lateral adjustment of the second mirror only, as well as detector tilt and focus position. For the evaluation of the tolerance sensitivity of the telescope we took those constraints on the compensators into account and applied the expected manufacturing tolerances from diamond-turning process (see Table 3).

Table 3. Assumed tolerance values.

Error	Value
Radius deviation	100 µm
Deviation of mirror distances	50 µm
Surface form error of the mirrors	120 nm r.m.s.
Decenter of M2 wrt. M1	10 µm
Tilt of M2 wrt. M1	1.8'
Decenter of M3 wrt. M1	5 µm
Tilt of M3 wrt. M1	0.12'

A Monte-Carlo analysis with 2000 equally spaced samples shows, that all simulated systems will have an average wavefront error below λ/14, which corresponds to diffraction limitation. 80 percent of all systems will be better than λ/20.

The results show clearly that the telescope may be manufactured with the foreseen diamond-turning process.

3. MECHANICAL DESIGN

The mechanical design of the telescope[7] is shown schematically in Figure 5. The observation direction is nearly perpendicular to the orientation of the sensor. According to IOF's "snap together" concept[3-6] the mirrors M1 and M3 share a common substrate. The additional fold mirror (marked M4) is mounted on top of the M2 substrate.

Both mirror substrates are decoupled from the telescope housing via sold-state hinges.

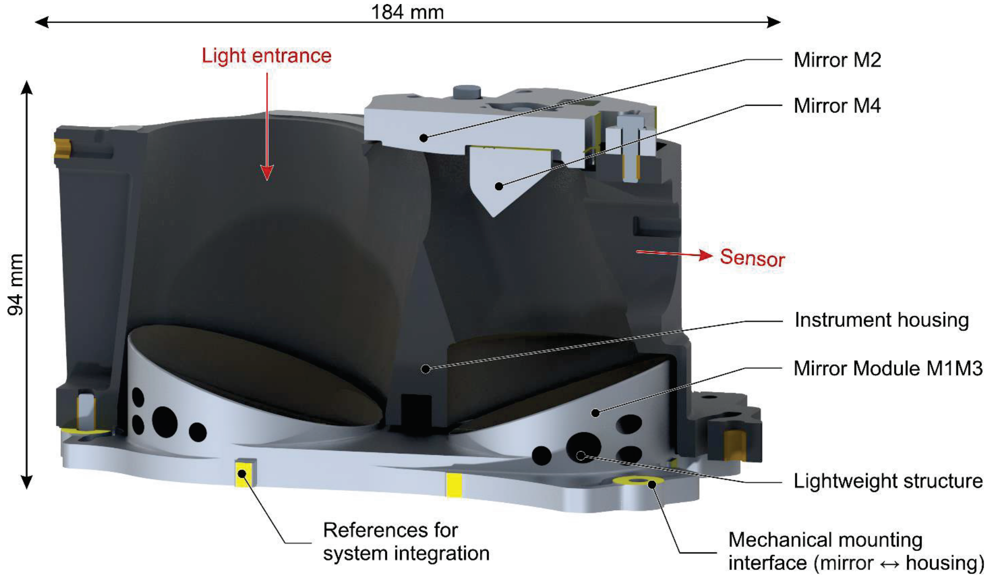

Figure 5. Mechanical layout of the TMA. Reference structures are marked yellow.

3.1 Mirror substrates

The combination of two mirrors on a common substrate considerably shortens the alignment process. However, it requires a change in the manufacturing strategy: Though the individual mirror surfaces are rotationally symmetric the combined duolith requires freeform technology using a synchronously moving tool. In order to evaluate the manufacturability, the cutting process has been simulated. The respective results for the stroke of the moving tool and the gradients in azimuthal and axial directions are shown in Figure 6. The values prove, that the design can be manufactured.

The realized mirror substrates are shown in Figure 7.

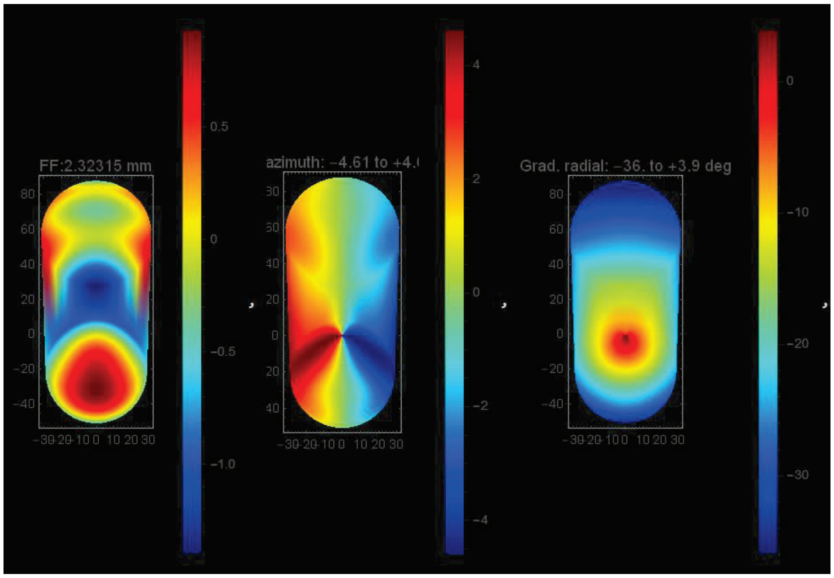

Figure 6. Analysis of manufacturability of the M1M3 duolith. The images show the stroke of the moving tool in mm (this corresponds to the freeform portion), the gradients in azimuthal and axial directions (in deg), respectively (from left to right).

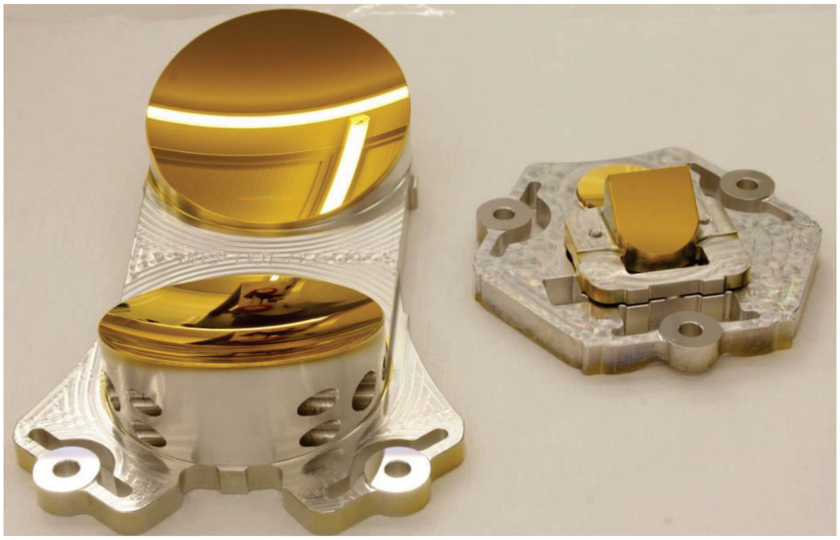

Figure 7. Realized mirror substrates. Left: M1 and M3 manufactured by freeform technology on a single substrate. Right: Fold mirror M4 mounted onto the M2 module.

3.2 Telescope integration

The mirror substrates carry mounting features as well as mechanical references which are manufactured by a milling process in the same run as the mirror surfaces. Typical position errors of the references with respect to the mirror surfaces are below 5 µm.

Similar diamond-cut structures made by fly-cutting are to be found on the telescope housing.

These references allow for a precise mechanical pre-alignment of the mirrors during integration. The respective position errors are of the order of 10 µm typically.

The final alignment by shifting of mirror M2 is done under interferometric control in a double-pass setup. Due to the precise pre-alignment only few iteration cycles are needed typically.

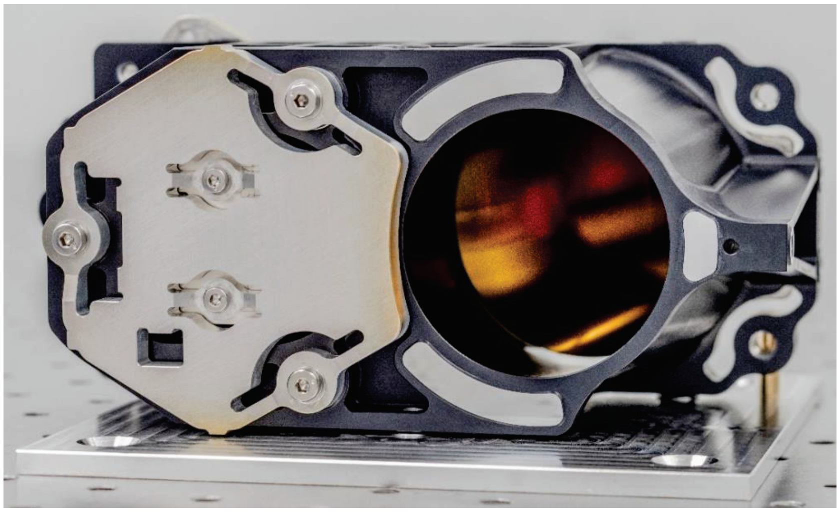

Figure 8. Telescope after integration.

The completed telescope after integration and alignment is shown in Figure 8.

4. SUMMARY

The instrument was launched successfully to ISS in February 2022 and is delivering reliable, high-resolution data with a ground resolution of 80 m. The realized telescope design allows for a diffraction limited performance at the design wavelength of 10 µm. The telescope fits into a design space of 80x80x150 mm³ which would correspond to appr. 1.5 U of a typical CubeSat. The opto-mechanical concept of the telescope allows for a cost-effective manufacturing and alignment.

5. ACKNOWLEDGEMENTS

The demonstrator design of the telescope was supported by the Free State of Thuringia in the framework of its initiative Digital Innovation Hub Photonics.

REFERENCES

[1] Korsch, D., “Closed Form Solution for Three-Mirror Telescopes, Corrected for Spherical Aberration, Coma, Astigmatism, and Field Curvature”, Appl. Optics 11, 2987 (1972).
[2] Korsch, D., “Closed-form solutions for imaging systems, corrected for third-order Aberration”, JOSA 63, 667 (1973).
[3] Scheiding, S., Damm, C., Holota, W., Peschel, T., Gebhardt, A., and Risse, S., “Ultra-precisely manufactured mirror assemblies with well-defined reference structures”, Proc. SPIE 7739, 773908, 2010.

[4] Risse, S., Scheiding, S., Gebhardt, A., Damm, C., Holota, W., Eberhardt, R., and Tünnermann, A., "Development and fabrication of a hyperspectral, mirror based IR-telescope with ultra-precise manufacturing and mounting techniques for a snap-together system assembly", Proc. SPIE 8176, 81761N, 2011.

[5] Beier, M., et al., "Development, fabrication, and testing of an anamorphic imaging snap-together freeform telescope", Appl. Opt. 54, 3530–3542 (2015).

[6] Peschel, T., et al., "Anamorphotic telescope for earth observation in the mid-infrared range", Proc. SPIE 10563, International Conference on Space Optics — ICSO 2014, 105631Y (17 November 2017); doi: 10.1117/12.2304168.

[7] Zettlitzer, L., et al., "Design and Fabrication of a miniaturized metallic telescope for earth observation", Proceedings of The 4S Symposium (2022).