

Metal-Optic Ritchey–Chrétien Telescope with Passive Drop-In Integration for a Compact Hyperspectral Instrument

Lucas Zettlitzer^a, Andreas Gebhardt^a, Nils Heidler^{*a}, Stefan Risse^a, Thomas Wettemann^b,
Ralf Münzenmayer^b, and Christophe Buisset^c

^aFraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany

^bAirbus Defence and Space GmbH, Willy-Messerschmidt-Str. 1, 82024 Taufkirchen, Germany

^cEuropean Space Agency, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

ABSTRACT

Compact hyperspectral payloads for small-satellite constellations require optical front-ends that combine high optical performance with short integration times and cost-efficient recurring production. This paper presents the design, manufacture, and integration of the Rainbow telescope, a compact athermal Ritchey–Chrétien metal-optic system operating from 450 nm to 1730 nm. Its core contribution is a manufacturing-driven, passive alignment concept for monolithic metal mirrors. Because each optical surface and its rotationally symmetric mounting references are generated in a single diamond-turning setup, the positional alignment of the mirrors is shifted from an iterative assembly step into the deterministic manufacturing chain, reducing the number of actively adjusted degrees of freedom of the two mirrors from ten to zero. Key design features are a monolithic secondary mirror unit that integrates mirror body, spider vanes, and ring mount in a single diamond-turned part, and an additively manufactured, support-free lightweight straylight baffle. The as-built mirror positions were achieved well within the allocated decentration and tilt budget, and the integrated breadboard complies with its spot-radius specification after purely passive, drop-in integration.

Keywords: Hyperspectral imaging, Metal optics, Ritchey–Chrétien telescope, Diamond turning, Alignment turning, Passive alignment, Additive manufacturing, Small satellite payloads

1. INTRODUCTION

The growing use of small satellites and distributed constellations in Earth observation is shifting the requirements for optical payload development. In addition to optical performance, compact spaceborne telescopes must increasingly meet demands for low mass, limited volume, short integration times, and cost-efficient recurring production. This is particularly relevant for missions with multiple identical flight units, where classical alignment-intensive assembly becomes a major cost and schedule driver.

A reflective telescope requires its mirrors to be positioned relative to each other with micrometer-level precision. Even small deviations in the lateral position (decentration), angular orientation (tilt), or axial spacing of a mirror degrade the optical performance of the system. It is useful to keep two conceptually distinct error sources apart throughout this paper: positional alignment denotes the placement of each optical surface with respect to the common optical axis (lateral, axial, and tilt degrees of freedom), whereas surface form denotes the figure of the individual mirror. In conventional practice, positional deviations are corrected by active alignment, an iterative process in which the position of each mirror is measured, adjusted, and re-measured until the optical performance meets the specification. Although well established, this process scales poorly to several identical units. Reducing the alignment effort therefore requires both error sources to be controlled by the manufacturing chain rather than recovered during assembly, which in turn requires optical design, manufacturing strategy, reference definition, and structural concept to be treated as a coupled system from the outset.

The telescope presented here has been developed within the Rainbow project, which targets a compact hyperspectral payload for agricultural and environmental monitoring (see Figure 1). Within this instrument,

^{*}Presenting author, nils.heidler@iof.fraunhofer.de

it serves as the optical front-end of a filter-on-chip architecture in which spectral selection is performed by a linearly variable filter mounted directly in front of the detector.^{1,2}

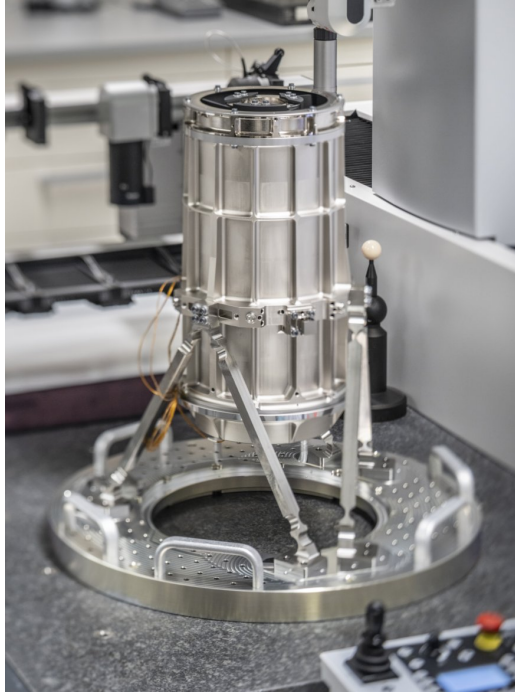


Figure 1: The integrated Rainbow telescope breadboard. Visible are the monolithic telescope housing with its circumferential stiffening ribs, the mirror M2 unit with integrated spider and M2 Baffle, and the bipod interfaces.

This paper focuses on the telescope realization as a compact, athermal Ritchey–Chrétien (RC) system based on precision metal optics and additively manufactured structural elements, integrated by passive alignment, following the principle of embedding alignment precision into the manufacturing chain rather than recovering it during assembly. This is made possible by a property specific to metal optics: the mechanical mounting references and the optical surface can be generated in the same diamond-turning setup, creating a direct, verifiable, and reproducible relation between them that is defined by the machine accuracy rather than by a subsequent alignment step. Conventional glass optics, in contrast, require a separate mechanical mount whose coordinate transfer typically introduces tolerances an order of magnitude larger, while the high specific stiffness and ductility of the metal substrate additionally allow compact decoupling structures and provide robustness against launch vibration.³ By machining the corresponding mating surfaces on the telescope housing with the same approach, the mirrors can be assembled by simple mechanical contact, with their positions defined entirely by the manufactured references.

Reference-based, alignment-reduced assembly of metal mirrors builds on this property and is well established. Snap-together concepts, in which optical surfaces and mounting interfaces are generated in a common machining setup, have been demonstrated for infrared (IR) and visible (VIS) freeform telescopes,^{3–7} and the same alignment-turning and drop-in integration principle underlies refractive space assemblies such as the ESA Sentinel-4 optical modules.⁸ The specific contribution of this work is to transfer this principle to monolithic metal mirrors in an on-axis Ritchey–Chrétien (RC) system for the VIS to short-wave infrared (SWIR) range. This is enabled by two elements. The axial degree of freedom is absorbed by tuning the housing length to the individually measured mirror radii, while the secondary mirror unit (see Figure 3) is realized as a single diamond-turned part comprising mirror body, spider vanes, and ring mount, avoiding additional mechanical interfaces along the reference chain. Combined with a consistently athermal design, this strategy removes the actively adjusted degrees of freedom of the mirrors entirely. The resulting concept and its verification are detailed in the following sections.

2. TELESCOPE DESIGN AND REQUIREMENTS

This section places the telescope within the Rainbow instrument, summarizes the optical and geometrical requirements derived from the mission, and introduces the athermal metal-optical design philosophy on which all subsequent manufacturing and integration decisions are based.

2.1 System context and derived requirements

The filter provides approximately 50 spectral bands between 440 nm and 1700 nm within a lateral extent of 10.24 mm and is described in detail elsewhere.^{1,9} In a classical dispersive imaging spectrometer such as *DESIS* a telescope images the observed scene onto a slit, and a subsequent grating spectrometer collimates the light, disperses it, and reimages it onto the detector.^{10,11} The filter-on-chip architecture retains only the front-end telescope and replaces the entire dispersive chain, so that the slit, the collimator, and the grating are no longer required, which is what makes the compact architecture possible. In return, the spectral assignment of each pixel is now defined solely by its lateral position on the filter, which shifts the burden of image quality entirely onto the telescope. By employing a purely reflective approach, the system provides high and spectrally uniform reflectance across the entire specified range, and inherently avoids chromatic aberration.

RC telescopes are well suited for filter-on-chip applications because they are aplanatic and provide a long focal length within a comparatively compact volume. Since coma is the dominant field-linear aberration of a classical Cassegrain telescope, its elimination in the RC configuration yields a rotationally symmetric and only slowly varying image quality across the field of view, which is essential for uniform illumination of the filter-on-chip detector. The remaining field curvature is of minor importance for this application, as it manifests only as a field-dependent defocus; it consumes tolerance budget but remains manageable. The uncorrected astigmatism is likewise accounted for in the design.^{12,13}

The telescope optics are based on a RC configuration with two mirrors, with the aperture stop located on the secondary mirror M2. The baseline optical design is shown in Figure 2. The present work targets a telescope for an instrument breadboard whose purpose is to demonstrate the overall system concept. The design is oriented toward a subsequent flight model. The telescope operates in a wavelength range from 450 nm to 1730 nm and has a nominal effective focal length of 828.0 mm.

A performance-critical specification is the spot size relative to the pixel and filter geometry. Throughout this paper, spot size is expressed as the root mean square (RMS) spot radius in the image plane. It must lie within a defined window. The spot must not be too small, to avoid undersampling and aliasing. It must not be too large, in order to maintain sufficient ensquared energy per pixel and to limit spectral crosstalk: because the central wavelength varies continuously along the filter, any lateral extent of the image spot is directly converted into a broadening of the sampled spectral band. For the steepest range of the Rainbow filter, the central wavelength changes by up to 159 nm mm^{-1} ,¹ so that the tolerable spot size follows directly from the acceptable spectral broadening.

In this particular system, the binding limit is not the maximum but the minimum spot radius: if the as-built spot becomes too small, the system must be able to be deliberately defocused prior to final integration to return into the allowed window. This is the direct motivation for the axial (z-distance) tuning of the housing to the measured mirror radii described in Section 4.1.

The tolerance values given in Table 1 were allocated based on the optical performance requirements of the telescope. The decentration and tilt tolerances describe the relative positioning of the mirrors. These values include contributions from mirror interface errors, i.e., misalignments between the optical coordinate system and the mechanical coordinate system, mechanical interface form deviations, and housing-related errors.

A further constraint inherent to any RC system is the central obstruction and the unavoidable obstruction introduced by the mechanical spider that secures the secondary mirror. This directly couples the optical requirements to the mechanical design of the M2 assembly and is therefore addressed together with the M2 realization in Section 3.4.

An overview of the mechanical design of the Rainbow telescope is shown in Figure 3. The optical subsystem housing is a tube located between the M1 and M2 mirrors, forming the central structural basis for the integration

Table 1: Allocated positioning and manufacturing tolerances

Error	Value
Radius error	$\pm 0.07\%$
Decenter	$\pm 20\ \mu\text{m}$
Tilt	$\pm 0.01^\circ$
Surface irregularity	$< 30\ \text{nm RMS (Clear Aperture)}$

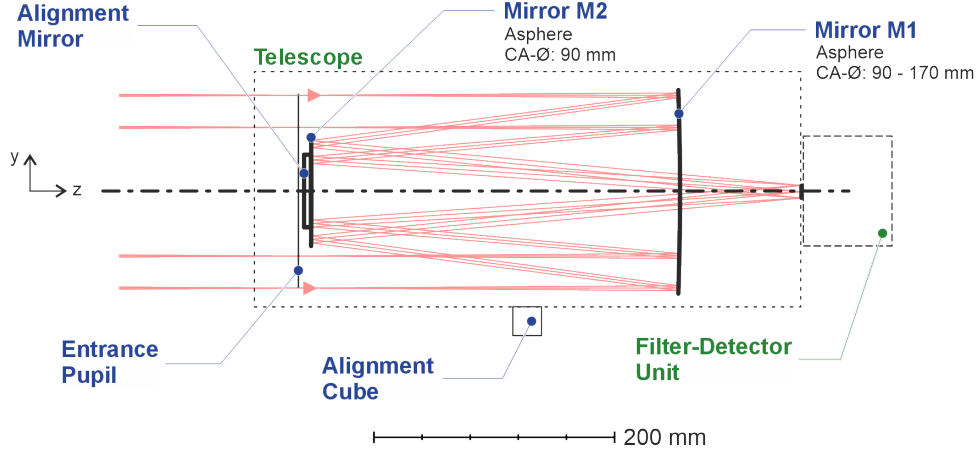


Figure 2: Optical design of the Rainbow telescope.

of the remaining telescope elements. The telescope baseplate is attached to the housing structure via rotationally symmetric references. The M1 Baffle is connected to the telescope baseplate, whereas the M2 Baffle is mounted directly to the M2 mirror. The rib structure of the housing was optimized in an iterative development process to balance lightweighting against mechanical stiffness under the specified loads. Circumferential strengthening ribs support the structure in the plane of the telescope’s center of gravity. The interface between the telescope housing and bipod is locally reinforced by a thicker central rib to increase stability in this plane. Additional interfaces for the filter–detector Unit, the entrance baffle, the alignment cube, and the measurement targets are implemented on the telescope baseplate, the housing structure, and the M2 mirror unit. The detailed realization of the housing is described together with the manufacturing chain in Section 3.6.

2.2 Athermal optical and opto-mechanical concept

To achieve an athermal design, materials with similar coefficients of thermal expansion (CTE) are chosen for both mirrors as well as for the telescope housing and baseplate.^{14,15} Consequently, a change in ambient temperature results in a simple scaling of the optical system without degrading its performance, although thermal gradients may still adversely affect it. The material choice is further driven by the optical performance requirements and the mirror manufacturing technology. The surface form error requirements of the mirrors can only be met by an additional figure-correction step using magneto-rheological finishing (MRF), which requires an amorphous nickel–phosphorous (NiP) layer to provide a hard, polishable plating. To prevent bimetallic bending, the CTE of the base material must be matched to that of the plating, which is achieved by adjusting the phosphorus content of the NiP layer.^{16,17} The preferred base material is therefore an aluminum–silicon alloy with a silicon content of at least 40 % (AlSi42), which additionally provides mechanical properties adequate for this application and, in particular, a higher specific stiffness than conventional aluminum. To maintain the athermal load path across mechanical joints, washers made of a material adapted to the AlSi42 CTE are used, while the bipods are made of TiAl6V4.

Accordingly, the telescope mirrors are designed as rotationally symmetric mirrors made from AlSi42, plated with NiP for shaping, figuring, smoothing, and corrosion protection. The mechanical mirror design follows a

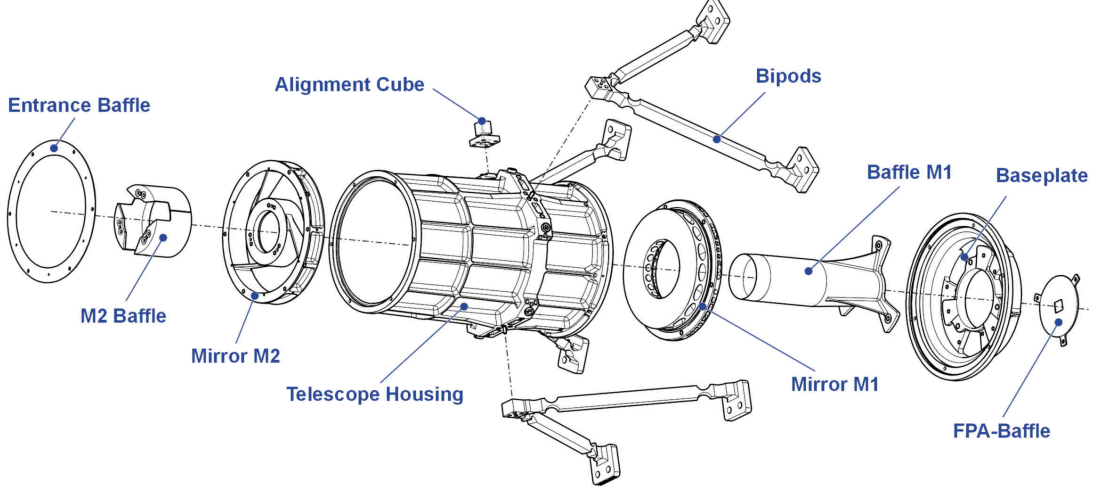


Figure 3: Exploded view of the Rainbow telescope showing the main components. Fasteners and auxiliary elements (screws, washers, bolts) are omitted for clarity.

snap-together assembly concept,⁴ which is the mechanical basis for the passive alignment strategy detailed in Section 3. The decoupling structures that connect the mirrors to the housing are intentionally designed to compensate mechanical and thermally induced forces without introducing thermal isolation, thereby minimizing temperature gradients within the system. As a result of this consistently athermal design, the optical performance is largely insensitive to homogeneous temperature changes and no dedicated thermal-management system is required.

3. MANUFACTURING-DRIVEN DESIGN FOR PASSIVE ALIGNMENT

The central idea of the Rainbow telescope is that positional alignment precision is a result of the manufacturing chain rather than of a separate, iterative adjustment step. This section therefore treats manufacturing and alignment strategy as a coupled system. It first describes the metal-optical process chain (Section 3.1) and the deterministic references it produces (Section 3.2). It then presents the component designs that were developed specifically to exploit this reference-based philosophy: the primary mirror unit M1 (Section 3.3), the monolithic secondary mirror unit M2 (Section 3.4), and the additively manufactured M1 Baffle (Section 3.5). Finally, it describes the telescope housing that carries all these components (Section 3.6). The way these references are used to achieve passive alignment during system integration is then described in Section 4.

3.1 Metal-optical manufacturing chain

The foundation of the passive alignment concept is an established process chain for ultra-precise metal optics, from NiP plating through diamond turning, MRF figure correction, chemical-mechanical polishing, and high-reflective coating. A particular feature is that the optical surfaces and their mechanical mounting references are generated in the same diamond-turning setup, thereby binding the references inherently to the optical axis. Fraunhofer IOF performs the entire process chain in-house. The 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.

Monolithic metal optics are susceptible to residual stresses induced during machining, which can lead to significant optical distortion. To mitigate this risk, the Computer Numerical Control (CNC) manufacturing chain is strictly divided into two primary stages: a pre-forming step and a final ultra-precision machining operation, separated by dedicated thermal stress-relief treatments. The lightweighting of the mirrors is integrated into the initial CNC machining stage. For M1, lightweighting is achieved through radial bores with a transitioning cross-section that is circular near the inner diameter and changes to an elliptical geometry toward the outer circumference. This transition ensures a constant radial web width between adjacent bores, which would otherwise

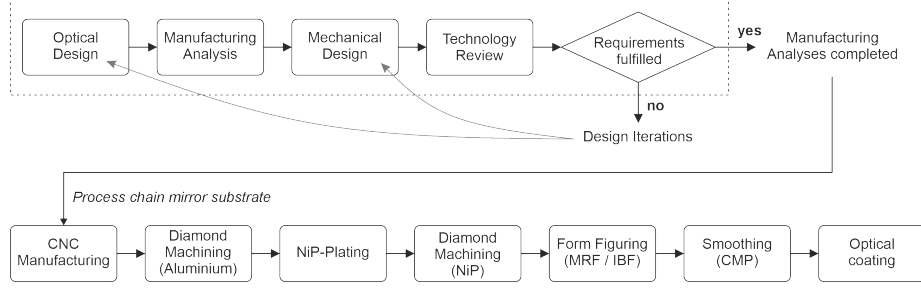


Figure 4: Simplified manufacturing chain of the mirror substrates with manufacturing analysis loop

increase toward the larger outer circumference. In contrast, the lightweighting of M2 is restricted to enclosed pockets located exclusively at the mechanical rim; these are intentionally closed structures to prevent stray and false light from compromising the optical path. No additional transverse bores were implemented for M2, as they would not have yielded a significant improvement in mass-reduction efficiency relative to the structural effort.

Once the substrates have been mechanically prefabricated and given a first thermal treatment, an ultra-precise diamond-turning (DT) process is performed. Both CNC-manufactured substrates were diamond turned in a similar sequence, starting with planarization of the substrate backside. This step is required for the subsequent machining of the optical side, during which the substrate is clamped with a specialized vacuum jig. The backside was lapped to a flatness below $1\text{ }\mu\text{m}$ peak-to-valley (PV),⁷ ensuring secure clamping and minimizing elastic stresses during DT machining of the optical surfaces. In the DT process, the optical surface and the mechanical interfaces are machined in optical quality within a single setup, ensuring a positional reference between the mechanical interfaces and the mirror surface of about $1\text{ }\mu\text{m}$.

Diamond machining allows the manufacture of ultra-precise mirrors, but the achievable surface roughness and the resulting periodic patterns limit their direct use to the infrared (IR) spectral range. By incorporating polishing techniques such as MRF and chemical mechanical polishing (CMP) after ultra-precise machining, the usable spectral range can be extended. In this context, the full aperture (FA) represents the fully manufactured optical surface, while the clear aperture (CA) is the part of the optical surface that must comply fully with the optical specification. The differentiation between FA and CA is intended to avoid edge effects during DT or polishing that could negatively affect image quality.

MRF is used for shape correction of mirrors M1 and M2 only. In conjunction with profilometric and interferometric surface-form-error (SFE) measurements, MRF iteratively reduces the low frequency surface form error (LSFE) and attenuates diamond-turning marks (micro-roughness). Chemical-mechanical polishing (CMP) is likewise applied only to M1 and M2. CMP is a smoothing process that produces a homogeneous and isotropic surface structure using a polishing machine with hard and soft polishing tools. Depending on the tools used, it affects the midspatial frequency errors (MSFE) or the surface roughness (HSFE) while leaving the overall figure quality unchanged. Finally, the optical surfaces of M1 and M2 are coated with a protected silver coating deposited by a magnetron-sputtering process. The surface qualities achieved by this process chain are summarized in Table 2; in particular, the residual micro-roughness of both mirrors is well below 1 nm RMS , which is a prerequisite for operation down to 450 nm .

In the final step, both mirrors (M1 and M2) are coated with a protected silver coating matched to the application wavelength range.¹⁸

Table 2: Surface qualities achieved for Mirror M1 and Mirror M2

	Mirror M1	Mirror M2
Form deviation	22.85	13.71
Roughness (spatial period range: $2\text{ }\mu\text{m}$ to $2000\text{ }\mu\text{m}$)	0.58	0.57

All values in nm RMS .

3.2 Deterministic reference concept

The passive alignment strategy rests on the single principle that each mirror carries mechanical references whose relation to its optical axis is fixed by manufacturing and can be verified. Because the rotationally symmetric mounting references are machined together with the optical surface in the same diamond-turning setup, they are inherently referenced to the optical axis of each mirror. These reference structures are subsequently used to assemble the mirrors onto the corresponding mounting interfaces on the telescope housing, ensuring that the optical axis of each individual mirror coincides with the optical axis of the system. This single, verifiable relation between optical surface and mechanical interface is the common basis shared by all component designs described below and by the passive integration strategy of Section 4.1.

3.3 Primary Mirror M1

A classical mount is required to secure the position of the mirror under changing environmental conditions. As a general rule, when designing an optical component mount, care must be taken to ensure that the wavefront is not adversely affected by the mounting forces, and that the wavefront aberrations do not exceed the permitted level.¹⁹ This is possible if the mounting does not introduce additional mechanical stress or if thermal loads are adequately compensated. In general, the mirror substrate must be stiffer than the decoupling structure connecting it to the telescope housing or otherwise, the mounting forces will deform the optical surface. The state of the art is an isostatic layout, which typically uses three discrete mounting points at 120° to connect the mirror to the housing.

As seen in Figure 5a, this classical approach could not be implemented for the M1 mirror. A conventional isostatic mount with discrete flexure joints would have been too space-consuming, as it requires significant lateral design volume. To comply with the strict envelope constraints of the application, a compact, monolithically integrated central-post (“mushroom”-type) decoupling geometry was used instead, which effectively decouples the optical surface from the mounting forces. The design was iteratively optimized to trade off lightweighting against mechanical stiffness under the specified loads. A customized hole pattern removes material from the neutral zone to further reduce mass.

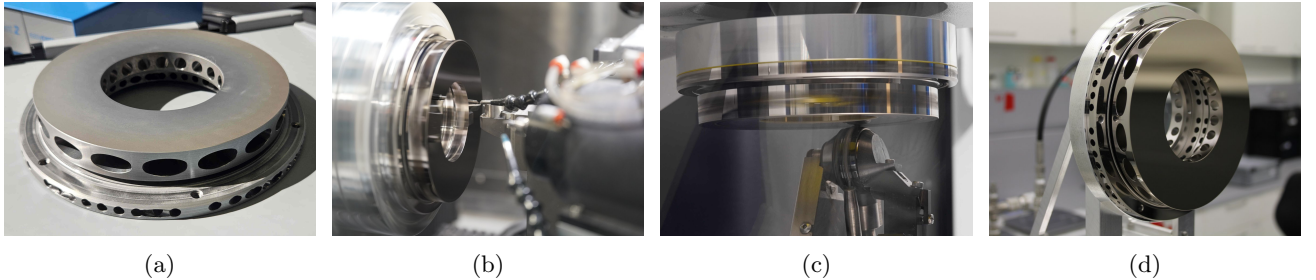


Figure 5: Manufacturing process chain of the primary mirror unit M1: (a) lightweighted substrate after final CNC-step, (b) after diamond turning, (c) after MRF, and (d) interferometric surface-form measurement of the finished mirror.

The mounting interface is kinematically overconstrained by using six screws instead of three. To prevent material strain and optical deformation under these conditions, the mating reference surfaces of both the telescope housing and the mirror unit are machined by diamond turning (detailed in Section 4.1). This manufacturing accuracy ensures that the degrees of freedom are precisely defined, minimizing clamping-induced stresses to a tolerable level.

Any residual surface deformation introduced by the overconstrained, monolithic interface is covered by the MRF figure-correction step that is part of the manufacturing chain in any case (Section 3.1), using metrology data acquired in the mounted state. Being a deterministic manufacturing operation rather than an iterative in-situ adjustment, it does not constitute positional alignment.

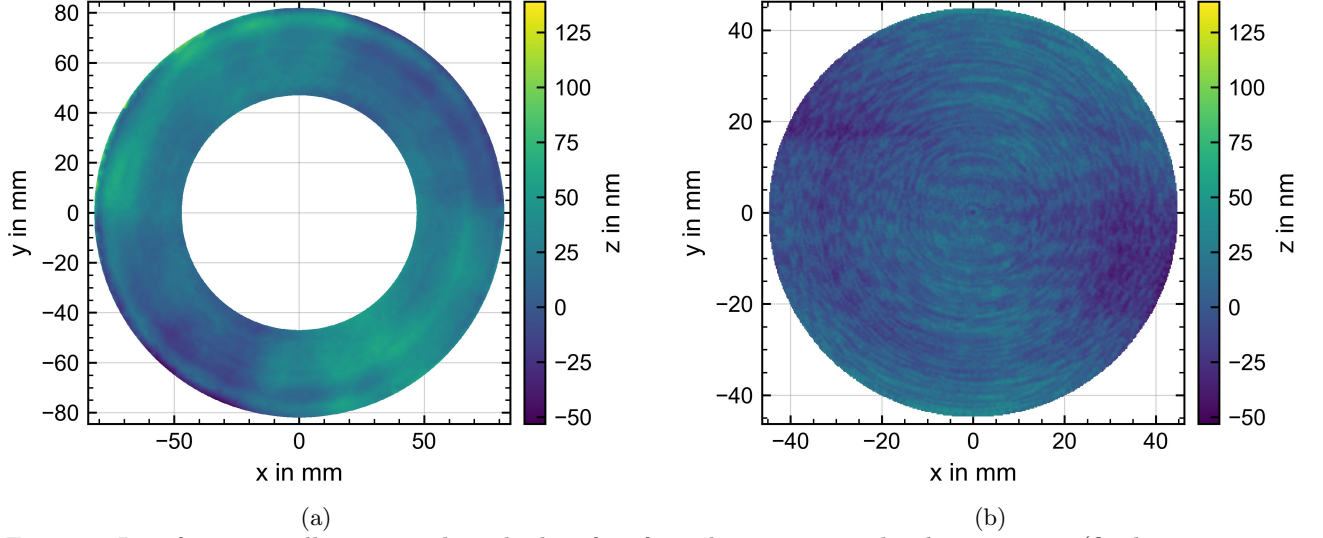


Figure 6: Interferometrically measured residual surface form deviation over the clear aperture (final measurement prior to integration). (a) Mirror M1 (22.85 nm RMS) and (b) Mirror M2 (13.71 nm RMS). Both mirrors comply with the surface-irregularity requirement of Table 1.

3.4 Secondary Mirror M2

As introduced in Section 2.1, the RC configuration entails a central obstruction and an unavoidable spider obstruction resulting from the mechanical mounting that secures the secondary mirror (M2) to the support structure. Beyond a slight reduction in overall throughput, the spider vanes introduce diffraction. Diffraction occurs inherently regardless of the vane geometry; the specific vane design merely alters the spatial distribution and appearance of the resulting diffraction spikes. The vane layout therefore results from a trade-off between structural stability, diffraction behavior, and manufacturing feasibility. A detailed stray-light and diffraction analysis is beyond the scope of this paper.

In principle, the technological implementation of RC secondary mirrors can be divided into two approaches: a split-part design, where the mirror substrate and the mechanical decoupling structure are separate components, and a monolithic design. Both concepts were initially evaluated. While a split-part assembly simplifies component handling between individual process steps, it introduces a longer tolerance chain between the optical surface and the reference structure. Furthermore, it requires an additional mechanical joint that must be carefully decoupled to prevent deformation of the mirror surface. This modular approach also demands a more massive structural design, particularly for the spider vanes, due to the inherently higher localized mass at the center of the mirror. In contrast, the monolithic approach inherently enables a more compact form factor, though it increases handling complexity during manufacturing. One example of this trade-off is the integration of both a highly reflective (HR) coating and a stray-light blackening on the same component, which would be considerably more straightforward in a split-part design but requires sophisticated process control in a monolithic block.

The monolithic architecture was selected, with the M2 mirror body featuring a geometry that decouples the optical surface from mounting forces within a single part. Following a load-driven optimization to minimize spider stresses under vibration loads, the mirror body, spider vanes, and ring mount were integrated into one monolithic component. Compared with the split-part variant, this offers improved resistance to vibration loads and enables direct referencing of the optical surface relative to the mounting interface. As for M1, rotationally symmetric references are machined alongside the optical surface in a single setup and are subsequently used to assemble M2 onto the mounting surfaces of the telescope housing. Additionally, the M2 mirror unit incorporates an alignment mirror surface for position and orientation measurements of the telescope, while a dedicated M2 baffle (consisting of three ring segments forming a tube) prevents stray light.

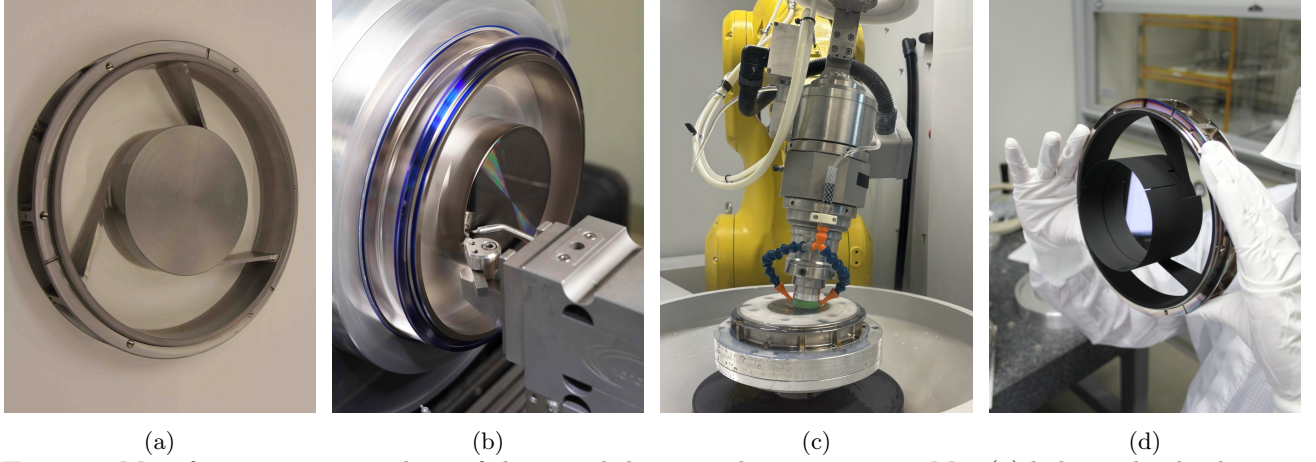


Figure 7: Manufacturing process chain of the monolithic secondary mirror unit M2: (a) lightweighted substrate after final CNC-step, (b) diamond turning, (c) CMP, and (d) integrated mirror and baffle M2.

3.5 Additively manufactured M1 Baffle

The primary-mirror baffle of the Rainbow telescope is additively manufactured. The M1 baffle is matched to the beam path in order to block direct stray-light paths and consists of a conical tube with a wall thickness of 2 mm, carrying a set of internal vanes and held by three ribs arranged at 120° intervals.

The main argument for additive manufacturing is the geometry itself. The combination of a high length-to-diameter ratio, thin walls, and internal circumferential vanes cannot be realized as a monolithic part by conventional cutting technologies, since the vanes are not accessible to a milling or turning tool inside the slender cone. A conventional realization would therefore have to be split into several joined segments, introducing further mechanical interfaces and potential stray-light leakage paths at the joints, analogous to the drawbacks that motivated the monolithic design of the M2 unit in Section 3.4. Selective laser melting (SLM) removes this restriction and is, for a component of this geometry, both the more economical and the more flexible option. Additive manufacturing of aluminum-silicon alloys with high silicon content has been established at Fraunhofer IOF for mirror bodies^{20,21} and for opto-mechanical structures;^{22,23} the M1 Baffle transfers this process chain to a stray-light component within an athermal metal-optical telescope.

The part design follows the constraints of the SLM process. Surfaces enclosing an angle of less than approximately 45° with the build plate require support structures to dissipate the process heat.²⁰ Since supports inside the closed cone could not be removed reliably afterwards, the inner vanes are angled such that they remain above this critical angle in the chosen build orientation. The vane inclination is therefore driven by two requirements at once: it blocks the direct stray-light paths, and it keeps the part printable without internal supports. For the same reason the interior remains fully open, so that the unfused powder can be extracted completely after the build.²⁰

The baffle material is AlSi42, consistent with the remaining structural components. Powder-bed-based SLM is a qualified process for this material and yields volume parts with a porosity below 0.05 %.²¹ After the build, the blank undergoes a stress-relief heat treatment and an ultrasonic cleaning step to remove adhering and enclosed powder.²²

Since the internal geometry is no longer accessible to tactile or optical inspection once the part is closed, it was verified by a computed-tomography scan (Figure 8b), following the quality-assurance approach established for additively manufactured opto-mechanical AlSi structures.²² The as-built SLM surface meets neither the dimensional nor the textural requirements of the functional interfaces,²² which are therefore CNC-machined afterwards (Figure 8c). This applies in particular to the interface plane between the telescope baseplate and the baffle's outer diameter, which is relevant for the integration described in Section 4.1. Finally, the baffle is coated with a thin NiP layer ($10\text{ }\mu\text{m}$) for corrosion protection. The layer is deposited on the interior surfaces as well,

in order to avoid electrochemical potential differences between the NiP and the AlSi substrate.²¹ A blackening layer is applied for further stray-light suppression.

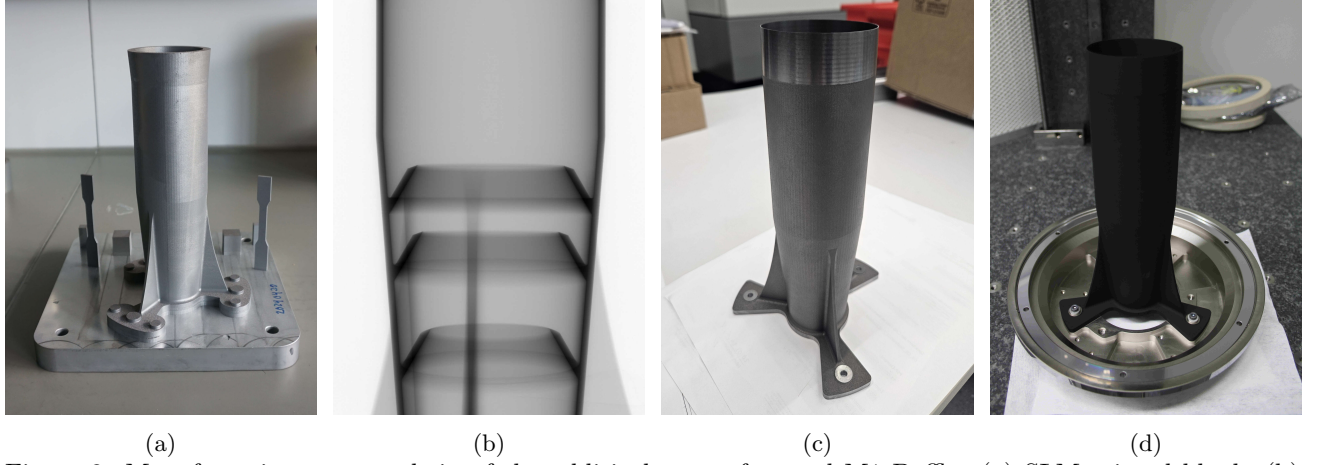


Figure 8: Manufacturing process chain of the additively manufactured M1 Baffle: (a) SLM-printed blank, (b) computed-tomography image of the inner vanes, (c) after the final CNC machining step, and (d) integrated and blackened baffle.

3.6 Telescope housing

The Telescope Housing carries all previously described components and closes the reference chain between M1 and M2. The instrument body was manufactured as a single monolithic housing using CNC milling, into which several references were subsequently machined by diamond turning. The design maximizes static and dynamic stiffness while minimizing mass through integrated lightweight structures. The inner contours wrap around the optical path to suppress stray light, and a black coating on the inside further improves the stray-light properties.

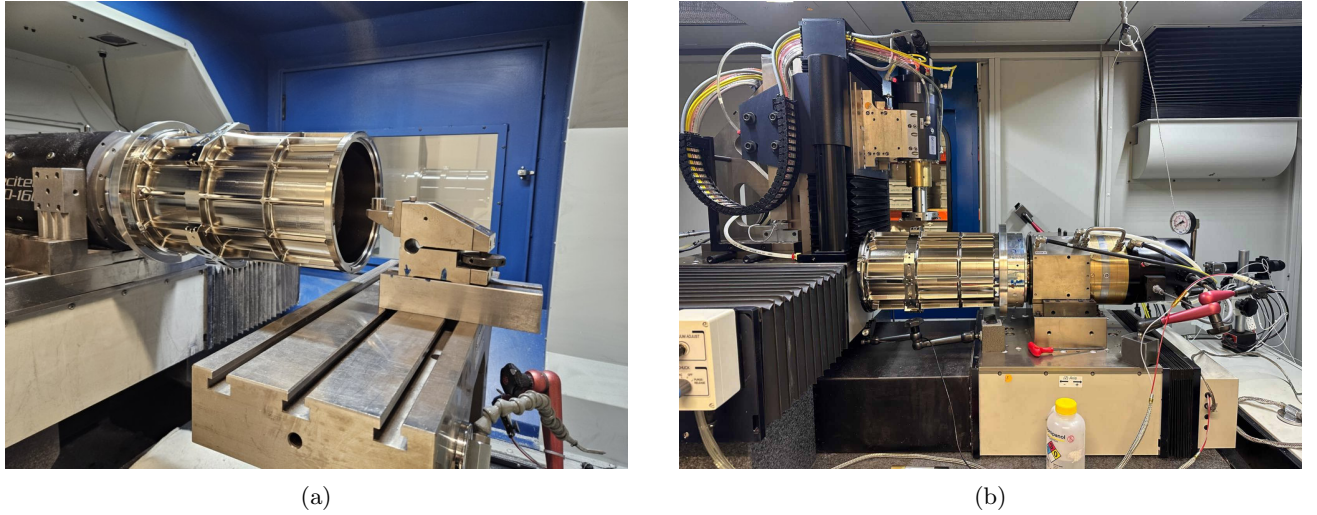


Figure 9: Diamond turning of the reference and interface surfaces on the telescope housing: (a) setup for mirror interfaces and (b) setup for alignment cube interface

By fly-cutting the lateral interface surfaces on a diamond milling machine (Figure 9b), the relation between these interface surfaces (which later define the optical axes) and the side references is realized with high precision. This is the manufacturing basis for the passive, drop-in integration described in Section 4.1.

4. INTEGRATION AND VERIFICATION

Building on the component designs and deterministic references introduced in Section 3, this section describes how the references translate into a passive alignment integration, and how the achieved alignment state is verified.

4.1 Integration concept

Alignment is one of the major cost and time drivers for classical reflective optical systems, where each asphere typically has to be aligned in five degrees of freedom, namely three translations (T_x , T_y , T_z) and two rotations (R_x , R_y). The drop-in approach followed here constrains these degrees of freedom from the assembly stage by coupling them during manufacturing, so that the achievable positioning accuracy is defined by the machine and measurement accuracy rather than by an alignment operation. For the two mirrors of the Rainbow telescope, the number of actively adjusted degrees of freedom is thereby reduced from ten to zero.

This passive concept applies to all mirrors and the telescope baseplate, which are integrated purely by drop-in. Only two non-optical auxiliary interfaces require an iterative adjustment step: The centering of the M1 Baffle on the telescope baseplate and the orientation of the alignment cube. Neither of which affects the positional alignment of the mirrors on the optical axis. Both are described at the end of this section.

The concept builds on the integration strategy established for refracting telescopes, e.g. the ESA Sentinel-4 mission.²⁴ Its basic principle is the ultra-precise machining of references and mounting surfaces to establish an exact relation between the optical and the mechanical coordinate systems of each optical element. For rotationally symmetric optics, this coordinate transfer is realized by diamond turning the optical housing to maximize coincidence between optical and mechanical axis.²⁵ This alignment-turning approach reaches tolerances below 1 μm for decentration, socket diameter, and vertex height.²⁵ The Rainbow telescope transfers this principle from refractive subassemblies to metal mirrors.

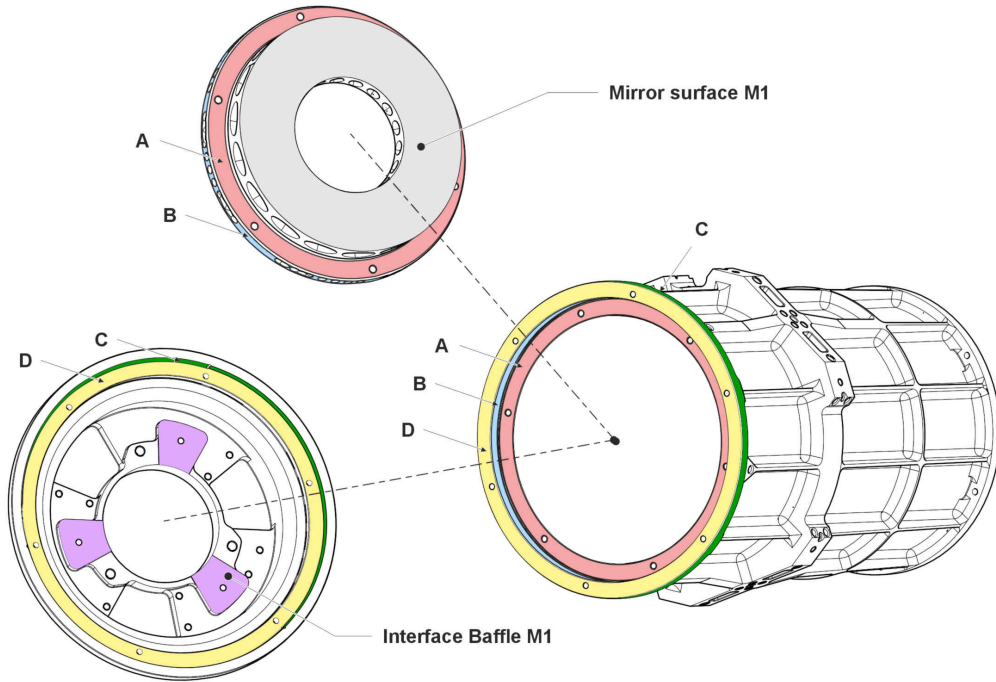


Figure 10: Simplified representation of the integration concept, illustrated for mirror M1 and the baseplate. Surfaces A and B and the mirror surface of M1 are machined in a single setup, as are the corresponding surfaces A and B on the housing. On the baseplate, surfaces C and D together with the M1 baffle interface are diamond-turned in one step.

Figure 10 illustrates the concept by means of mirror M1 and the baseplate. Within mirror M1, the reference surfaces A and B and the mirror surface itself are machined in a single machine setup, so that their mutual relation is defined by the machine accuracy rather than by a subsequent alignment step. The mating surfaces A and B on the housing are produced analogously (see Section 3.6). On the baseplate, surfaces C and D together with the M1 baffle interface are diamond-turned in one step. Mirror M2 and its interfaces follow the same reference concept, so that the description given here for M1 applies analogously to M2. In this way, a consistent reference system is established across the individual components, which forms the basis for the passive, drop-in integration described in the following.

Following the exploded view in Figure 3, the integration proceeds in a defined sequence:

1. The M1 baffle is centered and mounted onto the telescope baseplate.
2. The M2 baffle is mounted onto Mirror M2.
3. Mirror M1 is mounted onto the bottom side of the telescope housing.
4. Mirror M2 with integrated M2 Baffle is mounted onto the top side of the telescope housing.
5. The telescope baseplate with integrated M1 baffle is mounted onto the bottom side of the telescope housing.
6. Bipods and further elements are mounted to the telescope.

Lateral and tilt precision of the mirrors are achieved by stacking them onto their ultra-precise references with a tight fit. The as-built values are compared with the allocated tolerances in Table 3: the decentration remains below $5\text{ }\mu\text{m}$ and the tilt below 0.001° in the worst case, corresponding to a margin of a factor of four and ten, respectively, against the allocated budget. These values describe the mutual relation of the mechanical interface surfaces; the additional contribution of the optical axis with respect to the mechanical interface remains below $1\text{ }\mu\text{m}$, because the optical surface and its references are generated in the same diamond-turning setup. Since the mounting surfaces are machined in that same run, this snap-together integration of M1 and M2 requires no conventional active alignment.

In the axial direction, the telescope housing length compensates the radius errors of M1 and M2. Both radii are measured tactilely with a 2.5D profilometer (UA3P), and the required tuning length is derived from the measured radii. Taking into account the setting accuracy of the process and the vertex-height deviation of the mirrors with respect to their interfaces, this resulted in an axial correction of the housing length of $9\text{ }\mu\text{m}$ with respect to the nominal value. The nominal length includes margins on both sides accounting for manufacturing tolerances and measurement uncertainties. This axial tuning places the system within the specified spot-radius window and, if required, introduces a defined defocus to respect the minimum spot-radius limit introduced in Section 2.1.

Table 3: Allocated tolerances and as-built values of the mirror positioning. Decentration and tilt refer to the mutual relation of the mechanical interface surfaces, measured on a CMM.

Quantity	Allocated tolerance	As-built value
Decentration	$\pm 20\text{ }\mu\text{m}$	$< 5\text{ }\mu\text{m}$
Tilt	$\pm 0.01^\circ$	0.001° (worst case)
Radius error, M1	$\pm 0.07\%$	0.001%
Radius error, M2	$\pm 0.07\%$	0.001%
Axial housing tuning	—	$9\text{ }\mu\text{m}$ vs. nominal

The integration therefore reduces to the “drop-in” of the mirrors into the housing, using a tight, micrometer-range clearance and the mechanical mounting device originally developed for the Sentinel-4 optical module assembly.⁸ The device consists of a flat granite base carrying a vertical z-axis that holds and guides the housing during the drop-in. As no further alignment degrees of freedom are foreseen, the prediction based on the as-built mirror and housing data together with the optical design serves as the release criterion for the joining process. The only degree of freedom that remains selectable at integration is the azimuthal clocking (Rz) of the aspheres in six discrete steps of 60° . As a rotation about the optical axis, this clocking does not affect the positional alignment of a rotationally symmetric asphere and is therefore not part of the five positional degrees

of freedom addressed above. Rather than being adjusted iteratively during assembly, the clocking position is selected deterministically from the interferometrically measured surface data prior to joining, so as to orient the residual astigmatic contributions of the two mirrors against each other such that they partly cancel. It thus constitutes a feed-forward setting consistent with the manufacturing-driven philosophy, not an in-situ alignment operation.

Two auxiliary interfaces are exempt from the passive concept, neither of which affects the positional alignment of the mirrors on the optical axis. Prior to the mirror integration, the M1 Baffle was mounted onto the telescope baseplate and iteratively adjusted on a coordinate measuring machine (CMM) to minimize the decentration of the baffle, measured on the light-input side, with respect to the baseplate. The ultra-precision-machined inner diameter serves as the baseplate reference and is later used to center the baseplate on the telescope housing. Likewise, the alignment cube was first placed loosely on its interface; after tightening the screws it was iteratively adjusted in its x-rotation with respect to the alignment mirror, while all other orientations were defined by the ultra-precisely machined interface. Apart from these two interfaces and the bipods, all components follow the passive concept.

4.2 Verification approach

The verification does not target the wavefront error (WFE) as such, but the compliance of the as-built system with the specified spot-radius window introduced in Section 2.1, since this is the performance quantity that is directly relevant for the spectral performance of the Filter–Detector Unit (sampling, ensquared energy, and spectral crosstalk). Absolute values of the system wavefront error and of the resulting spot radius are subject to project confidentiality and are therefore not reported; the measured wavefront in Figure 11 is shown in normalized form, and all verification statements below are given relative to the allocated requirements.

Because the spot radius is not a directly measurable quantity, verification follows a two-step, model-based approach. First, the individual mirror radii are measured tactilely (UA3P) and the surface form errors are characterized interferometrically. These as-built data, together with the derived housing tuning length, are fed into the optical model to predict the resulting spot radius and to confirm that the system lies within the allowed window prior to final joining. Second, after integration the system wavefront is measured interferometrically at 633 nm in autocollimation against a plane mirror, using a 12-inch interferometer, and back-propagated through the optical model to derive the corresponding spot radius in the image plane.

The prediction based on as-built component data and the nominal optical design defines the expected performance and serves as the release criterion for the joining process, while the post-integration wavefront measurement provides an independent check of the achieved state. Because the RMS spot radius is not measured directly but derived through the optical model of an equivalent system, the predicted range and the derived as-built value are not expected to coincide exactly; the derived value lies above the predicted range, which is attributed to this model-based derivation. Compliance is nevertheless established, since in this system the binding criterion is the minimum spot radius, which is met with margin (see Figure 11).

The primary evidence for the deterministic reference concept is therefore geometric rather than photometric: the as-built decentration and tilt of both mirrors remain well within the allocated budget (Table 3), the axial compensation required was in the single-digit micrometer range, and no active positional alignment was performed at any point of the integration.

Based on this approach, the integrated Rainbow telescope was verified to comply with the specified spot-radius window after integration, without any active positional alignment step. These results were obtained on a single unit; statistical confirmation of the reference concept requires a series of builds and is the subject of future work.

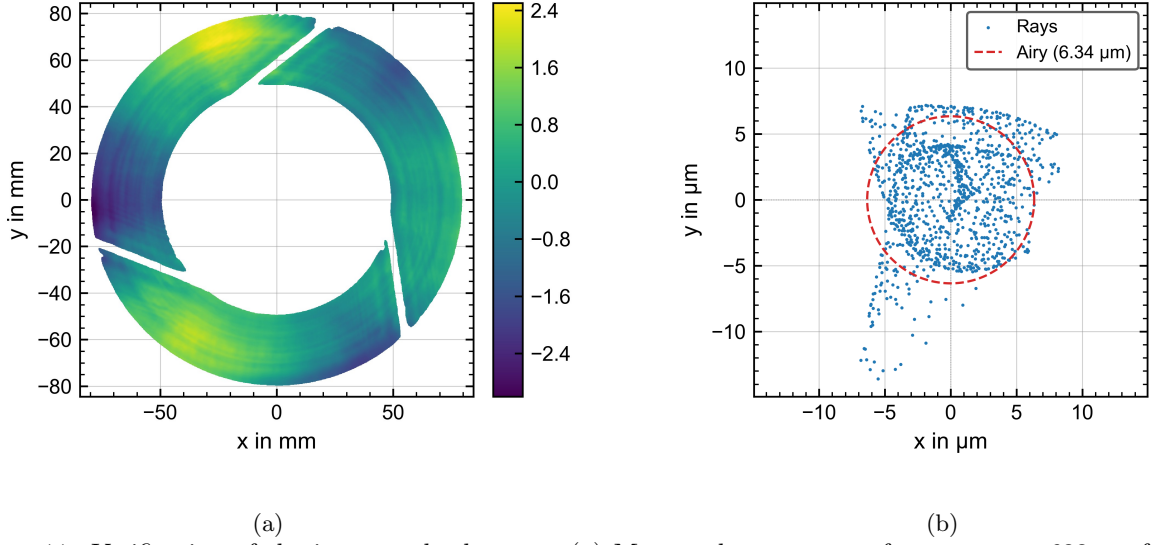


Figure 11: Verification of the integrated telescope. (a) Measured system wavefront error at 633 nm for a representative field point, shown in normalized form; the central obstruction and the spider vanes are visible. (b) Spot diagram derived from the optical model for the central field point, with the Airy radius indicated. The as-built system complies with the specified spot-radius window without active positional alignment.

5. CONCLUSION AND OUTLOOK

This paper presented the design, manufacturing, and integration of a compact, athermal RC metal-optic telescope developed as the optical front-end of the Rainbow hyperspectral instrument. The central contribution is a manufacturing-driven, passive alignment concept in which the positional alignment of the mirrors is shifted from an iterative assembly step into the deterministic manufacturing chain. By generating each optical surface and its rotationally symmetric mounting references in the same diamond-turning setup, a single, verifiable relation between the optical and mechanical coordinate systems is established. This transfers the alignment-turning and drop-in integration principle, previously established for refractive assemblies, to monolithic metal mirrors.

The consistently athermal material and interface design renders the optical performance largely insensitive to homogeneous temperature changes without a dedicated thermal-management system. The design comprises the monolithic secondary mirror unit M2, integrating mirror body, spider vanes, and ring mount into a single diamond-turned part, alongside the additively manufactured M1 Baffle, featuring a lightweight, support-free SLM geometry. The integrated telescope complies with the specified spot-radius window after purely passive, drop-in integration of the mirrors. The as-built decentration and tilt of the mirrors remain well within the allocated budget, with the axial compensation confined to the single-digit micrometer range, which confirms the validity of the deterministic reference concept.

One step of the current process remains breadboard-specific, namely the tuning of the telescope housing length to the individually measured mirror radii, which accommodates the manufacturing scatter of a first-of-its-kind assembly. Building on the data and experience gained here, the next step is to feed this knowledge back into the design by tightening the radius tolerances and by pre-compensating the mounting-induced deformation already in the nominal figure,^{15,26} so that neither the housing length nor the figure correction has to be adapted to the individual unit. This would enable true drop-in recurring manufacturing of identical units, which is the decisive economic driver for small-satellite constellations. In parallel, the maturation from breadboard to flight model will address environmental qualification, in particular vibration and thermal-vacuum testing, raising the concept from its current breadboard status toward flight readiness.

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