Design and implementation of an integrated and rapidly assembled infrared three-band optical system Postprint

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Abstract

Continuing advancement in astronomy, space exploration, and scientific detection, has increased demand for infrared multi-band detection systems. Traditional three-band optical systems, designed to simultaneously image at infrared short-wave, mid-wave, and long-wave bands typically rely on dispersive elements, leading to bulky sizes, complex system architectures, low efficiency, and challenges in rapid assembly. To overcome these obstacles, in combination with the latest third-generation infrared detectors, we propose a design for a compact and lightweight three-band optical system, with infrared capabilities in all three required bands. The core of this approach is an integrated design philosophy that emphasizes the high steepness of mirror surfaces. This design achieves uniform correction and optimization of chromatic aberration and off-axis aberration across the spectral range. We introduce a novel integration of optical and mechanical elements to replace traditional assembly, reducing manufacturing and assembly errors, and degrees of freedom, associated with high-power optical elements. Confirming the effectiveness through a combination of simulations and experimental comparisons, the measured mid-wave full-field transfer function exceeds 0.405 at 17 lp/mm, satisfying the imaging requirements of the system. The optical system is lightweight and compact, with a total mass under 408 g and a compact volume of just Φ112 mm × 117 mm. This serves as a valuable reference for the engineering application of high-performance, compact multi-band infrared composite detection systems for astronomy and space exploration.

Full Text

Preamble

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Design and Implementation of an Integrated and Rapidly Assembled Infrared Three-Band Optical System

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Abstract

Advancements in astronomy, space exploration, and scientific detection have driven increasing demand for infrared multi-band detection systems. Traditional three-band optical systems designed for simultaneous imaging in short-wave, mid-wave, and long-wave infrared bands typically rely on dispersive elements, resulting in bulky sizes, complex architectures, low efficiency, and assembly challenges. To address these limitations, we propose a compact, lightweight three-band optical system that leverages third-generation infrared detectors. The core of our approach is an integrated design philosophy emphasizing high-steepness mirror surfaces, which achieves uniform correction and optimization of chromatic and off-axis aberrations across the spectral range. We introduce a novel integration of optical and mechanical elements to replace traditional assembly methods, thereby reducing manufacturing and assembly errors as well as degrees of freedom associated with high-power optical elements. Through combined simulations and experimental validation, we demonstrate that the measured mid-wave full-field transfer function exceeds 0.405 at 17 lp/mm, meeting system imaging requirements. The optical system achieves a lightweight, compact form factor with total mass under 408 g and volume of just Φ112 mm × 117 mm, providing a valuable reference for engineering applications of high-performance, compact multi-band infrared composite detection systems in astronomy and space exploration.

Keywords: Three-band infrared; Integrated; Rapid assembly; Modulation Transfer Function (MTF)

1. Introduction

In recent years, the increasing complexity and diversity of detection and imaging targets have driven surging demand for multi-band real-time imaging detection systems. Multi-band infrared imaging technology offers enhanced adaptability to complex environmental conditions and improves detection, tracking, and recognition success rates compared to single-band infrared imaging systems[1-3]. Furthermore, multi-band infrared imaging systems can capture multi-dimensional spectral imagery, enabling collection of differential information across various wavelengths[4,5]. This facilitates acquisition of valuable target information, with spectral band fusion technology further enhancing imaging detection quality.

To date, most reported infrared multi-band imaging systems have been limited to dual-band configurations[6-9], which struggle to capture the full spectrum of radiation characteristics across short-wave, mid-wave, and long-wave spectral ranges. Multi-band optical systems commonly employ dispersive elements such as prisms and dichroic mirrors for light separation[10,11]; however, these elements suffer from coating efficiency limitations that cause loss of incident light energy, substantially reducing the energy reaching the photosensitive surface and necessitating larger optical apertures to ensure adequate information gathering. Consequently, multi-band composite optical systems tend to be bulky and complex, hindering widespread adoption.

In response to demands for rapid deployment, short development cycles, and cost-effectiveness in aviation, space, and astronomical applications, metal-based mirrors—particularly aluminum alloy mirrors—have emerged as promising solutions due to their high performance-to-cost ratio and have been integrated into space launch payloads[12-13].

With advancements in third-generation infrared mercury cadmium telluride (HgCdTe) detector technology, the light capture efficiency of multi-band optical systems has significantly improved, creating an urgent need for lightweight, rapidly deployable, and versatile multi-band composite imaging detection systems compatible with these new detectors. This paper presents a multi-band common optical path design aligned with the imaging mechanisms of third-generation detectors, aiming to achieve an ultra-compact infrared three-band system tailored for short-wave, mid-wave, and long-wave infrared targets commonly encountered in space detection imaging. Leveraging the efficient manufacturing capabilities of single-point diamond turning and adopting an integrated optical-mechanical design, we have developed a rapidly assembled three-band infrared optical system featuring a simple, compact structure with significant potential for application in aviation, space, and astronomical detection fields that demand miniaturization and mass production.

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2. Three-Band Optical System Design

2.1. Three-Band Imaging Working Principle

The operation of the three-band composite imaging optical system is illustrated in Fig. 1 [Figure 1: see original paper]. Third-generation infrared HgCdTe detectors enable multi-band layered imaging, with readout circuitry capable of distinguishing imaging information across various wavebands[14-16]. These detectors can disperse and color-separate incident light energy, allowing the novel detection system to achieve simultaneous imaging across all three bands with just a single optical dispersion. This simplifies the optical system design, enabling focus on optimizing imaging quality across a broad spectral range and on appropriate matching and selection of optical materials. The three-band infrared detector employs a common Dewar structure, where one band is imaged separately through beam splitting while the other two bands achieve co-focused imaging using a planar dual-color stacked detector. This detector comprises photosensitive elements absorbing different infrared bands, arranged or stitched on the same plane, enabling integrated design and manufacturing of devices for different bands in the same process.

2.2. Construction of the Initial Optical System Framework

The optical system design presented in this work encompasses three operational wavelength bands: short-wave, mid-wave, and long-wave infrared. The requirement for these bands to share a common focal plane poses a significant design challenge. Additionally, the broad operational wavelength range restricts optical material selection, with only a few materials—such as germanium, zinc sulfide, and certain chalcogenide glasses—being suitable for use.

The design process commences with preliminary selection of a catadioptric optical system configuration. We employ a two-mirror system in the R-C (Ritchey-Chrétien) configuration, favored for its ability to simultaneously correct both primary spherical aberration and coma. The structure is illustrated in Fig. 2 [Figure 2: see original paper], which compares it with the traditional Cassegrain configuration and provides a streamlined approach to establishing the initial system design. The focal point F_1 of the primary mirror is located behind the secondary mirror, with the portion blocked by the secondary mirror indicated by a red dotted line. In this two-mirror system, incident light rays (shown in red) reflect from the primary mirror to the secondary mirror and converge at the system focal point F_2. The semi-heights of the primary and secondary mirrors are h_1 and h_2, respectively, while d represents the distance between the primary and secondary mirrors. The distances from the vertex of the secondary mirror to the two focal points are l_2 and l_2', respectively, and f_1' denotes the focal length of the primary mirror. For the rear group, we select materials that meet three-band imaging requirements, while the front and rear groups are matched and jointly optimized[17].

Upon completing the initial front-group structure, we expand the imaging field to accommodate short-, mid-, and long-wave infrared requirements by using a combination of chalcogenide glass, multispectral ZnS, and Ge materials to achieve comprehensive and balanced aberration correction across all three bands. Furthermore, considering tolerances and manufacturability, the addition of high-order aspheric surfaces can enhance aberration correction capabilities, yielding a more compact optical-mechanical structure.

For a telephoto system with infinite object distance, the optical parameters are defined as follows:

- Object distance: $l_1 = \infty$, $u_1 = 0$
- Primary-secondary mirror interval: d
- Half-diameter of the primary mirror: h_1
- Half-diameter of the secondary mirror: h_2
- Blockage ratio: $\alpha = h_2/h_1$

For a two-mirror system where $R_2 = 2\alpha/(\beta + 1)$, we can derive the following relationships:

[Equations relating system parameters]

From these relationships, we obtain the optical system parameters. The initial parameters for the two mirrors are detailed in Table 1 .

Table 1. Initial parameters solution for two mirrors

Parameters	Mirror 1	Mirror 2
[Parameter definitions]	[Values]	[Values]

By substituting the parameters from the above equations into Equations (1)-(5), we derive the complete system specifications.

Fig. 2. Schematic diagram of initial optical design parameters for the R-C two-mirror system.

Key parameters include: secondary mirror magnification β, primary mirror conic coefficient e_1^2, secondary mirror conic coefficient e_2^2, Seidel spherical aberration coefficient S_I, Seidel coma coefficient S_{II}, Seidel astigmatism coefficient S_{III}, Seidel field curvature coefficient S_{IV}, and Seidel distortion coefficient S_V. The radii of the primary and secondary mirrors are R_1 and R_2, respectively.

For a two-mirror system, only five monochromatic aberrations require consideration. The third-order aberration coefficients corresponding to spherical aberration, coma, astigmatism, field curvature, and distortion are given by:

$$S_I = 2\sum_{i=1} h_i P_i + 2\sum_{i=1} h_i^4 K_i \tag{1}$$

$$S_{II} = 2\sum_{i=1} y_i P_i + J^2\sum_{i=1} W_i + 2\sum_{i=1} h_i^3 y_i K_i \tag{2}$$

$$S_{III} = 2\sum_{i=1} \frac{y_i^2}{h_i} P_i - 2J^2\sum_{i=1} \frac{y_i}{h_i} W_i + J^2\sum_{i=1} \phi_i + 2\sum_{i=1} h_i^2 y_i^2 K_i \tag{3}$$

$$S_{IV} = 2\sum_{i=1} \frac{\phi_i}{h_i} \tag{4}$$

$$S_V = 2\sum_{i=1} \frac{y_i^3}{h_i^2} P_i - 3J^2\sum_{i=1} \frac{y_i^2}{h_i^2} W_i + J^2\sum_{i=1} \frac{y_i}{h_i}(3\phi_i + \frac{\phi_i}{h_i}) + J^3\sum_{i=1} \frac{1}{h_i^2}\Delta\frac{1}{n_i^2} + 2\sum_{i=1} h_i y_i^3 K_i \tag{5}$$

If $S_I = S_{II} = 0$, we obtain the conditions for aberration correction.

2.3. Optical System Design Specification Parameters

In response to specific requirements for a three-band infrared detection system, we present an example design employing a detector with a 256 × 256 cryogenic focal plane array and 30 µm × 30 µm pixels. The design specifications are detailed in Table 2 . Imaging quality is characterized by the modulation transfer function (MTF).

Table 2. Parameters of the example optical system

Parameters	Specifications
Wavelength Bands	Short-wave: 2.5–2.9 µmMid-wave: 3.7–4.8 µmLong-wave: 7.7–9.5 µm
Field of view	3° × 3°
Focal length	146.5 mm
Optical system length	200 mm

Parameters	Specifications
Weight	
Image quality	Short-wave: MTF $\geq$ 0.40 @ 17 lp/mmMid-wave: MTF $\geq$ 0.35 @ 17 lp/mmLong-wave: MTF $\geq$ 0.30 @ 17 lp/mm

2.4. Design Results of the Optical System

The optical system employs a secondary imaging structure to achieve cold shield matching, with the intermediate image plane located between the primary and secondary mirrors. To minimize radiation from the mirrors themselves affecting detection performance, cold shield matching is a critical design consideration. The aperture stop is positioned at the detector’ s cold shield, and the entrance pupil is controlled to be as close as possible to the primary mirror, thereby reducing the effective diameter of the primary mirror. To enhance higher-order aberration optimization, the primary and secondary mirror surfaces are modified from quadratic to higher-order aspheric surfaces.

Considering the design specifications, system obscuration requirements, and overall length constraints, the initial optical system structure is optimized. Due to the impact of central obscuration on the optical transfer function, the mirror surfaces are controlled to achieve an obscuration ratio better than 1:4 while meeting system image quality requirements.

We use the CODE V software package to optimize the initial structure. The completed optical system is shown in Fig. 3 [Figure 3: see original paper]. The system comprises a two-mirror assembly (primary and secondary mirrors), a lens correction group, and a detector assembly. Incident light reflects off the primary and secondary mirrors, then passes through the lens group to form an image on the detector focal plane. The detector is divided into two photosensitive surfaces: reflected light acts on photosensitive surface FPA1, while transmitted light acts on photosensitive surfaces FPA2 and FPA3.

The lens focal length combination follows a positive-negative-positive-negative-positive sequence using IG24-ZnS-IG24-Ge-IG24 materials. These lens materials can be rapidly machined using single-point diamond turning. Following design refinement, the surface obscuration is optimized to 22.6%. The total length of the optical system, measured from the secondary mirror to the detector window, is meticulously controlled at 104.5 mm, with the tube length ratio maintained around 0.7, creating an ultra-compact three-band system design.

We evaluate the imaging capabilities of the optical system at the Nyquist frequency (17 lp/mm) across the three wavelength bands: short-wave infrared (2.5-2.9 μm), mid-wave infrared (3.7–4.8 μm), and long-wave infrared (7.7–9.5 μm), as shown in Fig. 4 [Figure 4: see original paper]. Considering MTF variation across the full field of view, we establish five fields of view (C1-C5) for evaluation. For the short-wave infrared band (2.5-2.9 µm), the edge field MTF exceeds 0.65 at the Nyquist frequency. For the mid-wave infrared band (3.7-4.8 µm), the edge field MTF exceeds 0.58 at the Nyquist frequency. For the long-wave infrared band (7.7-9.5 µm), the edge field MTF is better than 0.3 at the Nyquist frequency. The MTF of the optical system approaches the diffraction limit, with 100% cold shield matching efficiency, ensuring excellent imaging quality.

Fig. 4. Three-Band optical MTF curves, with the x-axis showing spatial frequency and the y-axis showing normalized MTF. C1-C5 correspond to the MTF curves of different fields of view respectively. (A) Long-wave MTF curves. (B) Mid-wave MTF curves. (C) Short-wave MTF curves.

2.5. Tolerance Allocation Results

Rapid assembly of optical systems can reduce manufacturing costs, necessitating careful consideration of tolerances during the design phase. To enable rapid assembly, it is crucial to validate that the optical system possesses reasonable tolerance margins, making it essential to estimate the tolerance impact domain and identify sensitive tolerance items.

Given inevitable manufacturing and alignment errors in production, the three-band infrared optical system’ s manufacturing errors include tolerances for surface figure error, radius error, and quadratic coefficient error. Alignment errors encompass decentration, tilt, and spacing errors for mirrors and lenses. Since the optical system is coaxial and rotationally symmetric, only radial decentration and axial spacing displacement require consideration. During optical system alignment, the primary mirror (P-M) serves as a fixed reference, requiring analysis only for manufacturing errors during tolerance analysis. Alignment tolerances must be considered for the secondary mirror (S-M) and lens group.

The surface obscuration in this system is optimized through Monte Carlo analysis using CODE V software to evaluate tolerances. Subsequently, tolerances are adjusted to reasonable ranges based on engineering feasibility and redistributed for evaluation[18].

Achieving rapid manufacturing and quick assembly characteristics for the three-band infrared optical system represents a crucial objective. While meeting image quality requirements for infrared three-band imaging, it is necessary to reduce the optical system’s tolerance sensitivity, decreasing dependence on assembly accuracy and facilitating rapid assembly. Tolerances are readjusted and allocated from both manufacturing and assembly perspectives to ensure good feasibility in production and assembly processes. The preset tolerance values are listed in Table 3 .

Table 3. Tolerance assignment results for the optical system

Index	Figure error	Radius error	Quadratic coefficient error	Spacing error	Decenter
P-M	0.07λ (λ=632.8 nm)	0.02 mm	Reference	-	-
S-M	0.07λ (λ=632.8 nm)	0.02 mm	Reference	0.02 mm	0.015 mm
Lens	0.07λ (λ=632.8 nm)	0.01 mm	Reference	0.02 mm	0.015 mm

After establishing the tolerance distribution, we assess MTF across diverse fields of view for the short-wave, mid-wave, and long-wave infrared bands, accounting for the defined tolerances. Within these predefined tolerance bounds, the short-wave band can maintain MTF ≥ 0.37 with 97.7% probability. For the mid-wave band, MTF is expected to exceed 0.45 with 97.7% probability, while the long-wave band is projected to achieve MTF > 0.38 with 97.7% probability. The tolerance MTF curves are shown in Fig. 5 [Figure 5: see original paper].

Fig. 5. Monte Carlo tolerance analysis results for the three-band infrared optical system after adding optical tolerances. C1-C5 correspond to the wavefront differential tolerance analysis curves of different fields of view respectively. (A) Probability curve showing long-wave MTF reduction. (B) Probability curve showing mid-wave MTF reduction. (C) Probability curve showing short-wave MTF reduction.

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3. Rapidly Assemblable Opto-Mechanical Structure Design

Given the optical system' s small tube length ratio, an ultra-compact structural layout is necessary to achieve a lightweight and miniaturizable opto-mechanical structure. With growing application and advancement of metal optics, the trend toward integrated opto-mechanical design is increasingly demonstrating its benefits. First, metal optics can be rapidly processed using single-point diamond turning (SPDT), enabling fabrication of complex aspheric surfaces. Second, the backplate support structure is directly integrated into the metal mirror with pre-designed connection holes.

This approach facilitates joint design of the mirror body and support structure, eliminating the need for additional tightening screws or adhesive bonding layers. Moreover, using the same material for both the mirror body and support structure eliminates thermal expansion coefficient mismatch, facilitating realization of an athermal optical system. This simplifies opto-mechanical design complexity while enhancing component environmental adaptability[19].

3.1. Overall Configuration of the Structure

The thin catadioptric optical system poses specific challenges for spatial arrangement of mirrors and structural components. Ultra-compact layout and integrated design represent effective strategies for achieving lightweight, miniaturized systems[20,21].

The optical system in this study employs a coaxial catadioptric configuration with a very short distance between the primary mirror and rear lens group. Consequently, the primary mirror support structure and lens group are arranged in a radially spaced, staggered layout. The optical surface of the primary mirror and structural components are designed using an integrated approach that combines the secondary mirror support with the secondary mirror tube, the primary and secondary mirrors with the support backplate, and the primary flange with the lens tube. This design reduces component count from 10 in traditional designs to 6, improving assembly efficiency while minimizing assembly errors and degrees of freedom. The basic composition of the opto-mechanical structure is depicted in Fig. 6 [Figure 6: see original paper].

Fig. 6. Opto-mechanical structure of catadioptric optical system. (A) Schematic diagram of components designed for conventional structures. (B) Schematic diagrams of components designed for our newly proposed structures that can be rapidly assembled.

3.2. Integrated Mirror Structure Design

The design must ensure the mirror body possesses high rigidity to prevent deformation under static and dynamic loads. Additionally, the mirror support structure must provide thermal and mechanical stress isolation between the mirror surface and external mounting interface. To enhance mirror assembly adaptability to external environments, a flexible hinge structure is required to dissipate thermal and mechanical loads.

For aerospace environments with significant thermal and mechanical loads, maintaining mirror position stability is crucial and can be achieved using a high-torque mounting mechanism. For this optical system, to ensure rapid mirror assembly, we propose an integrated mirror design structure focusing on three specific aspects.

First, threaded holes on the mirror body should be avoided as they can cause issues such as uneven thread straightness, thread gaps, and machining errors that directly affect final mounting surface quality and introduce installation stresses. Second, adequate clearance must be maintained between the mounting surface and mirror. If axial space is limited, a flexible hinge slot should be considered to increase the force transmission path and reduce sensitivity to mirror surface quality changes. Third, a flexible structure can accommodate installation torque, ensuring stresses are released during mounting.

In accordance with these principles, we have designed a flexible hinge structure capable of accommodating large installation torques. This structure integrates the mirror body with the flexible hinge, allowing the hinge to deform along the tangential direction of screw preload to dissipate installation stresses. A three-dimensional model of the aluminum alloy mirror is shown in Fig. 7 [Figure 7: see original paper].

Fig. 7. 3D model of the primary mirror structure design, with three-dimensional axes shown by XC, YC, and ZC. (A) Front view of the mirror. (B) Back view of the mirror.

3.3. Integrated and Optimized Design of Support Structures

Given the structural layout and weight constraints of the optical system, optimized design of the secondary mirror support tube is essential. A commonly employed method is material topology optimization, which strategically removes non-load-bearing material. The Solid Isotropic Material with Penalization (SIMP) model—a variable-density approach for solid isotropic materials with penalties—is a prevalent optimization technique for continuous structure topology optimization. This method employs a stiffness constraint to minimize structural volume during optimization[22,23].

The support structure optimization is a static optimization problem where the objective function minimizes structural compliance (or maximizes stiffness by minimizing strain energy), with structural volume ratio serving as the constraint function. The mathematical model for this[24] is given by Equations (13) and (14).

$$\min : C = F^T U = U^T K U \tag{13}$$

where C is the mirror compliance (objective function minimizing strain energy), K is the global stiffness matrix, U is the global displacement vector, F is the global load vector, F^T is the transpose of F, and U^T is the transpose of U.

$$\text{s.t.} \begin{cases} KU = F \\ V(\rho_i) = V_0 f \leq 0 \\ 0 < \rho_{\min} \leq \rho_i \leq 1 \end{cases} \tag{14}$$

where s.t. denotes the optimization constraints, ρ is the unit density, V is the design domain volume constraint, f is the volume fraction, and V_0 is the design domain volume.

We use the optimization module of the HyperMesh software package (Altair, Troy, Michigan, USA) to complete topology optimization analysis under given boundary constraints. Based on the ultra-compact optical system layout and topology optimization results, the topology-optimized secondary mirror support is modeled for engineering implementation, yielding the final secondary mirror support structure shown in Fig. 8 [Figure 8: see original paper].

Fig. 8. Support design model based on topology optimization. (A) Density contour map of the topology optimization, where blue indicates material removal and red indicates material retention (the red ring near the base is outside the designed area). (B) 3D model of the lens barrel remodeled based on optimization results.

4. Analysis of the Feasibility of Lightweight Manufacturing and Rapid Assembly Mirrors

Metal mirrors with apertures of 200 mm or less can achieve surface flatness better than $1/10\lambda$ (where $\lambda = 632.8$ nm) using single-point diamond turning (SPDT). To further improve surface precision, careful consideration of forces acting on the mirror during manufacturing is essential. A primary mirror with a significant thickness ratio (diameter to thickness) must be evaluated for manufacturability and ease of assembly, as these factors are critical for three-band optical system creation.

During SPDT processing, mirror surface quality is primarily influenced by centrifugal deformation and flatness deformation from mirror mounting. Forces affecting the mirror during processing are typically dominated by centrifugal forces and single-point tooling cutting forces, which range from approximately 0.3 to 1.5 N[25]. For mirrors with rotationally symmetric structures and adequate support rigidity, processing stresses can be considered negligible.

4.1. Analysis of Machining Centrifugal Forces

We analyze deformation during the primary mirror’ s single-point diamond turning process. By removing rigid body displacement and tilt, surface shape fitting is performed using the MATLAB software package (MathWorks, Natick, Massachusetts, USA), with results shown in Fig. 9 [Figure 9: see original paper].

We find that the primary mirror’ s flexibility is particularly well-suited for rotational turning on a single-point diamond lathe. Despite its structural flexibility, centrifugal deformation generated during the diamond turning process is minimal, with the primary mirror’ s root mean square (RMS) deformation measuring only 0.66 nm, indicating excellent rapid manufacturing processability.

Fig. 9. Centrifugal force analysis result of SPDT. (A) Displacement contour diagram showing centrifugal deformation. (B) Mirror deformation contour of the primary mirror after removing the displacement and rotation of the rigid body. Red shows large displacement, and blue represents downward displacement.

4.2. Rapid Assembly Flatness Adaptability Analysis

In addition to processing deformation, final mirror surface quality must also account for installation effects[26]. We analyze primary mirror flatness adaptability under typical installation conditions using a three-point mounting configuration at positions A, B, and C. The simulated installation conditions are divided into three cases:

Case 1: Installation point A has 3 μm flatness, B has 0 μm, and C has 0 μm.
Case 2: Installation point A has 3 μm flatness, B has 1 μm, and C has 0 μm.
Case 3: Installation point A has 3 μm flatness, B has 2 μm, and C has 0 μm.

Given typical single-point diamond turning operating conditions with a spindle speed of 500 RPM, we conduct centrifugal force analysis. The final results are presented in Fig. 10 [Figure 10: see original paper]. The primary mirror demonstrates good adaptability to 3 μm flatness installation, satisfying infrared optical system installation requirements.

Under different installation conditions, mirror installation deformation varies, with best adaptability occurring when a single point is either raised or depressed. For rapid assembly, yield rate must be considered, requiring determination of worst-case deformation based on assembly tolerance requirements. The least favorable situation corresponds to three-point installation where one point serves as a reference zero while the other two exhibit high and low deviations, respectively, causing wave-like surface deformation.

This extreme condition provides more reliable analysis results. It is also evident that controlling planar consistency of at least two installation points can effectively reduce installed mirror surface deformation.

Fig. 10. Cloud maps of RMS deformation on the primary mirror surface after removing rigid body displacement and rotation (red indicates large deformation, blue indicates small deformation). (A) Case 1 condition, (B) Case 2 condition, and (C) Case 3 condition.

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5. Rapid Manufacturing Adaptability and Assembly Verification

5.1. Rapid Manufacturing of the Mirror

The primary and secondary mirrors are fabricated using single-point diamond turning (SPDT). During manufacturing, mounting surface flatness is meticulously controlled, and an auxiliary support method is employed to further reduce centrifugal deformation effects on the mirror surface. As shown in Fig. 11 [Figure 11: see original paper], the turned mirrors achieve surface flatness better than $1/20\lambda$ (where $\lambda = 632.8$ nm). The mounting surface and mirror surface are machined in the same clamp, ensuring perfect matching between mirror surface tilt and rear mounting. This unifies the processing and alignment reference, reducing subsequent optical system alignment complexity. During optical alignment, only centration and decentration adjustments are necessary, eliminating mirror tilt adjustment and significantly simplifying the alignment process.

Fig. 11. Processing, measurement process, and measurement results of the primary mirror. Red shows large deformation, and blue shows small deformation. (A) The completed primary mirror. (B) Test results of the surface shape of the primary mirror, including RMS and Peak and valley (PV) profile errors, power errors, and sample sizes.

5.2. Rapid Installation Adaptability Verification

To verify the simulation analysis conclusions from Section 4.2, we conduct rapid installation plane adaptability validation on the primary mirror under the three installation conditions described in the simulation analysis. This verifies primary mirror adaptability under different planarity conditions using three-point installation. The primary mirror installation surface is ground and treated to simulate various planarity conditions that may occur during installation. Interferometric surface profile tests are performed on the primary mirror under installation conditions 1, 2, and 3.

The surface accuracies of the primary mirror (shown in Fig. 12 [Figure 12: see original paper]) under all three installation conditions meet the specified tolerance requirement of 0.07λ ($\lambda = 632.8$ nm). Under installation condition 1, the primary mirror surface change is 0.012λ (7.6 nm); under condition 2, the change is 0.025λ (15.8 nm); and under condition 3, the change is 0.019λ (12.0 nm). Measurement discrepancies arise from challenges in artificially creating installation planarity defects that perfectly match simulated conditions; however, installation planarity change pattern consistency can be assessed from observed trends. The test results confirm that the primary mirror exhibits good surface adaptability under 3-micron planarity installation conditions, validating that the flexible primary mirror design is more adaptable to demanding installation environments such as wave-like surface deformation. During mirror installation plane machining, controlling consistent planarity of at least two installation points can effectively reduce mirror surface deformation after installation, providing clear guidance for engineering, manufacturing, and implementation.

Fig. 12. Flatness adaptability verification results. Red shows large deformation, and blue shows small deformation for the primary mirror. (A) case 1 conditions, (B) case 2 conditions, and (C) case 3 conditions.

6. Optical System Performance Testing

The optical lens is precision-assembled on the collimator, yielding a three-band infrared system with total weight of just 408 g and compact volume of only Φ112 mm × 117 mm. Following alignment and adjustment, we conduct comprehensive performance testing of the entire system. System MTF is measured using a specialized transfer function measuring instrument with a mid-wave infrared detector.

Detailed test results are shown in Fig. 13 [Figure 13: see original paper]. The tangential MTF is 0.50 @ 17 lp/mm, and the sagittal MTF is 0.405 @ 17 lp/mm. The discrepancy arises from one lens exceeding surface accuracy tolerance, though still meeting the requirement that mid-wave MTF exceed 0.4. Due to project schedule constraints, the lens surface error was not corrected. The optical system meets stringent requirements for high-quality three-band imaging.

Fig. 13. Medium wave infrared MTF test. The red curve shows the meridian MTF curve, and the blue curve shows the sagittal MTF curve. Inset are sample points of the transfer function curve. (A) Photograph of the optical system being tested. (B) MTF curves of the measured optical system by software screenshots.

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7. Conclusions

To meet imaging detection requirements across short-wave, mid-wave, and long-wave infrared spectra, we present an ultra-compact, lightweight three-band optical system. Based on third-generation detector imaging technology, the system enables simultaneous co-focused imaging across all three infrared bands.

Initially, drawing upon third-generation multi-color detector imaging principles, we develop a design methodology for a three-band co-focused optical system. Starting with a two-mirror system using chalcogenide glass optical materials, we achieve a wide-tolerance optical system. To enhance assembly efficiency, we introduce an integrated design approach for optical and structural components, leveraging rapid manufacturing characteristics of metal mirrors and topological optimization to minimize assembly part count and degrees of freedom. We confirm rapid assembly capabilities through simulations and tests. The assembled optical system achieves total weight under 408 g with compact volume of only Φ112 mm × 117 mm. The full field-of-view transfer function in the mid-wave infrared band exceeds 0.405 @ 17 lp/mm, satisfying stringent imaging requirements.

Our system offers distinct advantages over traditional multi-band infrared optical systems, including compact and lightweight design, broad tolerance range, and quick assembly capability. The design and fabrication of this optical system provide a valuable reference for advancing lightweight, miniaturized multi-band infrared optical systems for aerospace and astronomical exploration applications.

Author Contributions

Shuanglong Tan conceived the ideas, designed and implemented the study, and wrote the paper. Lin Ma collected meteorological tropospheric delay data, performed statistical analysis, and revised the paper. Guangwei Shi provided data for optical design scheme selection. Yulin Wang and Shuaiwei Mu performed experiments. Xin Zhang completed design validation. All authors read and approved the final manuscript.

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Declaration of Interests

The authors declare no competing interests.

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Note: Figure translations are in progress. See original paper for figures.