

KT90+: assembly and verification approach for a compact CubeSat telescope

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ABSTRACT

Compact off-axis three-mirror telescopes are attractive for CubeSat Earth observation, but their image quality is sensitive to mirror placement, focal-plane attitude, and stray-light paths. This paper presents an integrated assembly and verification workflow for KT90+, an engineering evolution of the Taiwan Space Agency's approximately 2U, 92-mm-aperture Korsch telescope. A coordinate measuring machine (CMM) transfers optical-component coordinates to a persistent external target-ball network, enabling interferometric alignment of the roof mirror and tertiary mirror and subsequent placement of the focal-plane assembly. Together with finite-element analysis, this CMM framework guided selection of a low-deformation magnetic mounting interface. The final 35-term Fringe Zernike fits yielded root-mean-square (RMS) wavefront errors of 0.0502, 0.0927, and 0.0902 waves at image-plane field positions $X = 0, +5, \text{ and } -5$ mm, respectively. Through-focus contrast transfer function measurements were used to select the final focal-plane assembly focus, yielding 0.12 at 0.93 times the sensor Nyquist frequency. Reverse ray tracing guided the addition of targeted baffles and light traps; with the main-path flux normalized to unity, the simulated stray-light flux was more than three orders of magnitude lower than that of KT90. A two-metre reverse-projection screen test, supported by high-dynamic-range imaging and photometer sampling, provided a hardware diagnostic of residual leakage paths. The workflow connects coordinate transfer, wavefront verification, focal-plane alignment, and stray-light inspection for compact CubeSat telescopes.

Keywords: CubeSat telescope, Korsch telescope, optical alignment, coordinate transfer, wavefront error, contrast transfer function, stray light, reverse projection

1. INTRODUCTION

The demand for finer ground-sampling distance in Earth-observation missions drives optical payloads toward longer effective focal lengths and wider corrected fields while satellite volume and mass remain constrained. Compact off-axis reflective telescopes are well suited to these requirements because their optical paths can be folded without introducing chromatic aberration. In particular, the Korsch three-mirror anastigmat (TMA) can provide a compact package with a wide, well-corrected field [1]. At CubeSat scale, however, small rigid-body errors of the powered mirrors and image sensor can introduce substantial aberrations. Mirror edges, structural openings, and pupil-related paths may also produce unwanted irradiance at the detector. Achieving the nominal optical prescription is therefore insufficient; assembly, alignment, focal-plane integration, and stray-light verification must be treated as a connected process.

KT90 is a compact Korsch-type telescope developed by the Taiwan Space Agency (TASA) for the ONGLAISAT CubeSat. The published instrument has a 92-mm aperture, a 725-mm effective focal length, a 2.2-degree field of view, and an optical path packaged within approximately 2U [2]. ONGLAISAT was launched in November 2024 [3]. During the KT90 ground campaign, the measured contrast transfer function (CTF) was 0.17 before environmental testing and 0.12 after thermal-vacuum and vibration testing, compared with a predicted value of 0.31 at 50 line pairs per millimetre [2]. The published on-axis root-mean-square (RMS) wavefront error (WFE) was 0.1474 waves. These results demonstrated the feasibility of the architecture but also exposed a gap between the modelled and measured contrast and highlighted the cost of alignment iterations that were not tied to a persistent instrument coordinate frame.

KT90+ was built as an engineering article to improve assembly control, focal-plane integration, and stray-light suppression while retaining the compact Korsch architecture. The M1-M2 pair forms an intermediate image, which permits interferometric verification of that subassembly before downstream components are installed. The intermediate image alone, however, cannot establish the full six-degree-of-freedom relationship of the roof mirror, M3, and focal-plane assembly (FPA) to the M1-M2 pair. A process was therefore required that linked mechanical placement to optical verification and preserved the relationship through mirror bonding.

Previous alignment studies for off-axis multi-mirror systems have used aberration-sensitivity models based on Zernike coefficients [4]. Other work has incorporated well-defined mechanical reference structures into precision mirror assemblies [5]. Coordinate measuring machine (CMM) methods can further connect optical components and image sensors to a common instrument frame, as demonstrated for the FORMOSAT-8 focal-plane assembly [6]. In KT90+, measured optical and tooling coordinates are transferred to target balls accessible after installation. Coordinate placement provides the initial state; interferometric wavefront measurements then verify the assembled optical state and guide the remaining allowable adjustments.

The image sensor is positioned initially within the same coordinate framework, and its focus is selected using through-focus CTF. In parallel, reverse ray tracing is used to identify unwanted paths, which are suppressed with dedicated M1 and M2 baffles, a pupil-stop light trap, and a roof-mirror light trap. Reverse-projection measurements and high-dynamic-range (HDR) image synthesis are used to inspect the residual spatial distribution. This design-analysis-build-test loop follows the general practice of combining stray-light modelling, targeted baffling, and hardware verification for nanosatellite instruments [7].

This paper describes the integrated KT90+ workflow and reports its engineering results. The contribution is the connection of four verification layers: CMM coordinate transfer, interferometric optical-system alignment, CTF-based focus selection, and screen-based reverse-projection inspection. Together, these layers provide a traceable sequence from component placement to image-plane and stray-light assessment.

2. KT90+ ARCHITECTURE AND VERIFICATION STRATEGY

2.1 KT90 heritage and redesign objectives

The KT90 optical train comprises the aspheric primary mirror M1, aspheric secondary mirror M2, a roof mirror (RM), and an off-axis aspheric tertiary mirror M3. The published system uses a 92-mm aperture, 725-mm effective focal length, 2.2-degree field of view, 0.31 obscuration ratio, and visible-band operation from 400 to 900 nm [2]. The reflective train is folded into an approximately 10 x 10 x 20 cm optical-path envelope. Figure 1 shows the principal opto-mechanical elements and the separation of the mirror, main-plate, substructure, and FPA hardware.

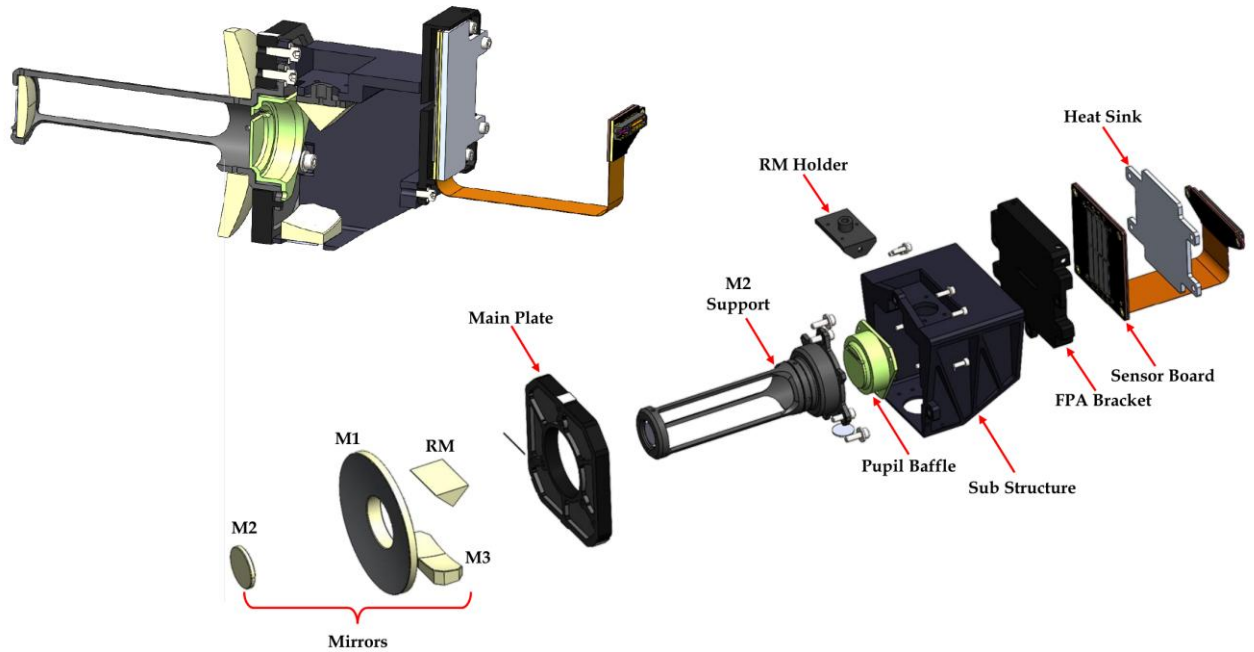


Figure 1. KT90/KT90+ opto-mechanical architecture. The cross-section shows the folded Korsch path; the exploded view identifies M1, M2, M3, the roof mirror (RM), main plate, M2 support, pupil baffle, substructure, FPA bracket, sensor board, and heat sink.

KT90+ retains this architecture but changes how it is assembled and checked. The redesign objectives were: (1) to establish a coordinate frame that remains accessible throughout integration; (2) to reduce the deformation introduced by temporary magnetic tooling; (3) to combine coordinate placement with interferometric verification rather than using either alone; (4) to select focus for an industrial line-scan camera using through-focus CTF; and (5) to add targeted suppression features for the dominant stray-light paths. The article was developed to validate the integration and inspection methods.

2.2 Coordinate transfer using target-ball metrology

During system integration, the optical vertices and axes cannot be directly and repeatedly probed by the CMM. Precision target balls are therefore used as measurable surrogate fiducials. Their centers can be measured repeatedly from different directions, allowing the optical references of M1, M2, and M3 to be transferred to the mechanical assembly and alignment equipment.

The CMM measures the target balls associated with M1, M2, and M3, together with those on the main plate and the interferometer fixture. Using the established relationship between each target-ball set and its corresponding optical or mechanical datum, all measured coordinates are transformed into a common instrument coordinate frame. The resulting position and orientation errors are then used to command the hexapods, which place the mirrors and interferometer at their design coordinates.

The target balls retained on the main plate preserve this coordinate reference and provide an accessible datum for the subsequent installation and alignment of the FPA.

To reduce fixture-induced mirror deformation, the magnetic mounting interface was refined from KT90 to KT90+. The final low-deformation configuration was selected using CMM assessment and finite-element analysis (FEA).

Figure 2 shows the baffle and light-trap hardware, magnetic fixture, and assembly station. The station integrates CMM access, hexapod positioning, and an interferometer around the telescope article. This arrangement allows the same external target-ball network to be observed during mechanical placement and optical verification.

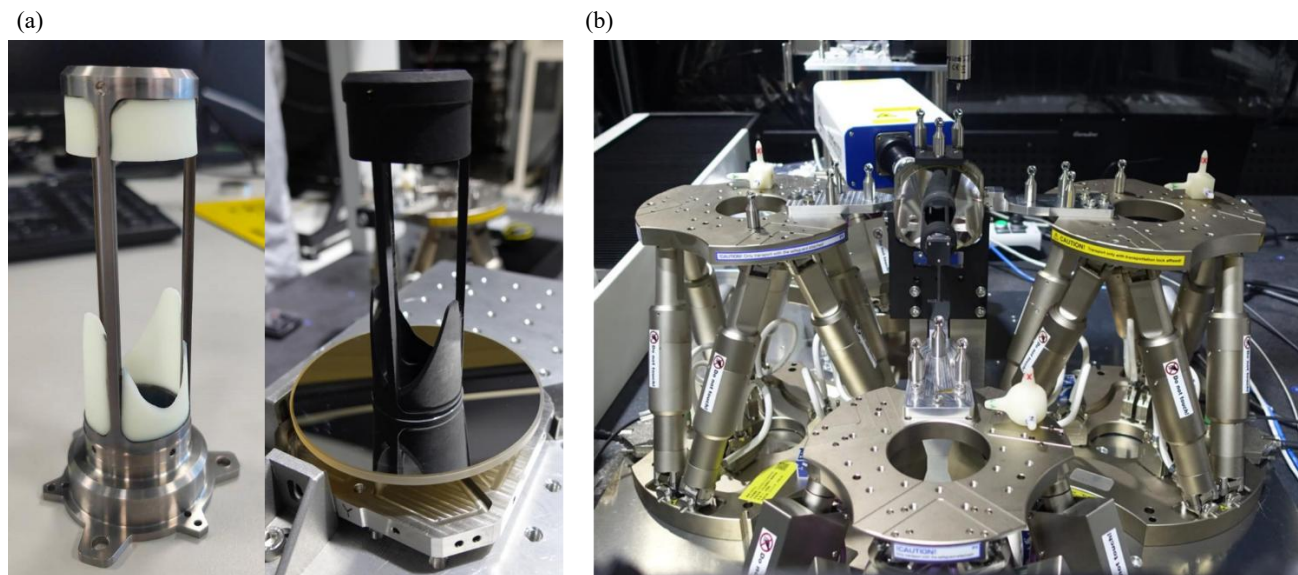


Figure 2. KT90+ alignment hardware and station: (a) M2-baffle and blackened light-trap hardware; (b) assembly station combining CMM target balls, hexapod positioning, and interferometric verification.

3. ASSEMBLY AND VERIFICATION METHODS

3.1 Optical-system assembly and coordinate transfer

The optical system was assembled sequentially using interferometric alignment and CMM-based coordinate transfer. M1 was installed on the main plate, and M2 was aligned with a six-axis hexapod in a double-pass interferometric setup before

bonding. Target-ball measurements then transferred the common instrument coordinate frame to the M3, roof-mirror, and interferometer fixtures.

After M3 and the roof mirror were installed, the complete M1–M2–RM–M3 path was aligned interferometrically. The M3 and roof-mirror translations were retained at the CMM-transferred coordinates, while the remaining correction was applied in tilt to preserve the nominal geometry used for stray-light analysis. The mirrors were bonded and verified after curing, and selected internal surfaces were blackened to suppress stray light.

3.2 Interferometric wavefront verification

Final wavefront verification was performed interferometrically at image-plane field positions $X = 0$, $+5$, and -5 mm using 35-term Fringe Zernike fits. Figure 3 shows the fitted maps, and Table 1 summarizes the peak-to-valley (PV) and root-mean-square (RMS) WFE results.

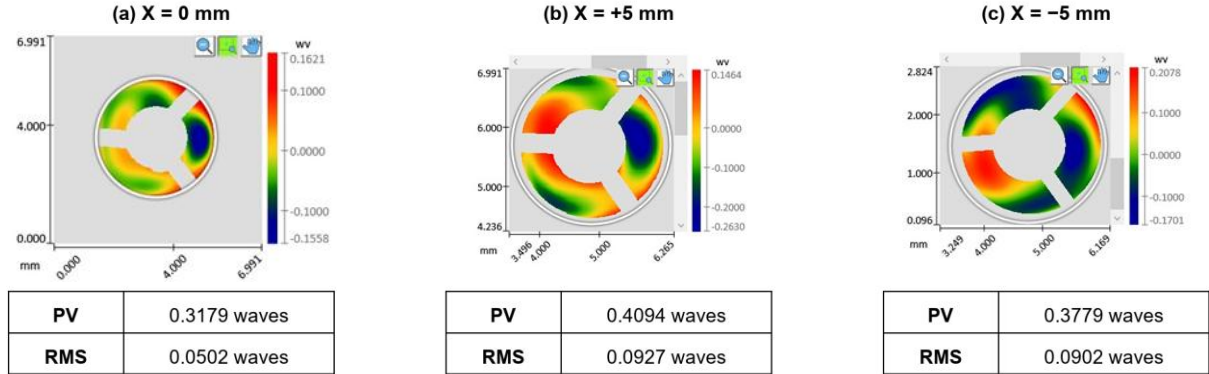


Figure 3. Final 35-term Fringe Zernike fitted wavefront maps at image-plane field positions (a) $X = 0$ mm, (b) $X = +5$ mm, and (c) $X = -5$ mm.

3.3 Focal-plane focus selection by through-focus CTF

After coarse placement using the CMM target-ball network, the FPA attitude was adjusted with a collimator-projected slit at the on-axis and symmetric off-axis field points, targeting an image width of approximately two pixels. Through-focus CTF measurements of a periodic bar target were then used as the focus-selection metric, following the method previously applied to the FORMOSAT-8 FPA [6]. At each axial position, CTF was calculated as $CTF = (I_{max} - I_{min}) / (I_{max} + I_{min})$; Figure 4 shows the test configuration and representative traces used for focus selection. Six focus positions at 0.05 mm intervals were sampled.

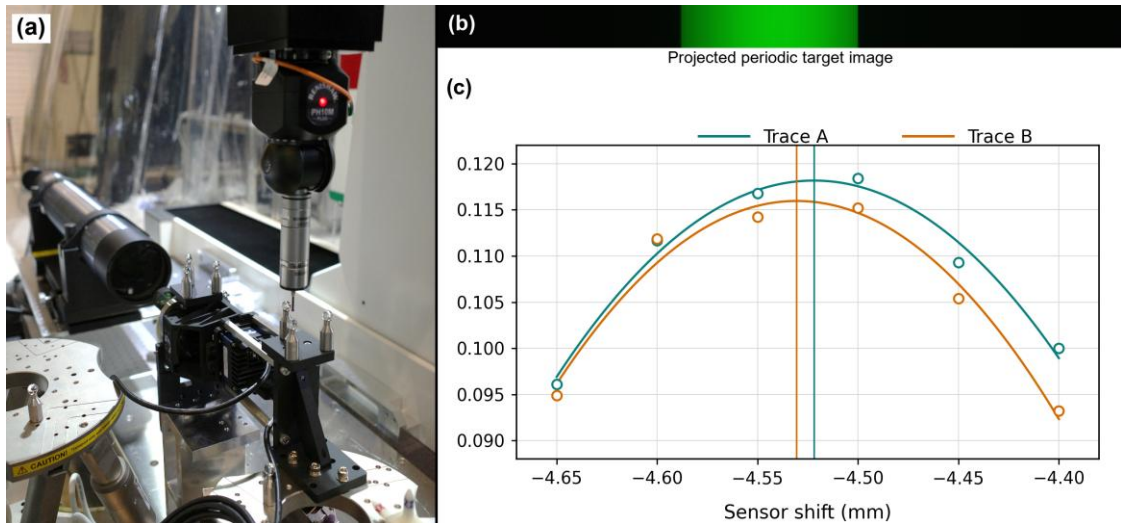


Figure 4. FPA focus selection: (a) test setup, (b) projected target image, and (c) through-focus CTF traces.

3.4 Stray-light modelling and reverse-projection inspection

Reverse ray tracing of the KT90 geometry identified stray-light paths near the M2 support and roof mirror. The KT90+ design therefore incorporated M1 and M2 baffles, a pupil-stop light trap, and a roof-mirror light trap. Figure 5 compares the two configurations under the same simulation settings with the main-path flux normalized to unity.

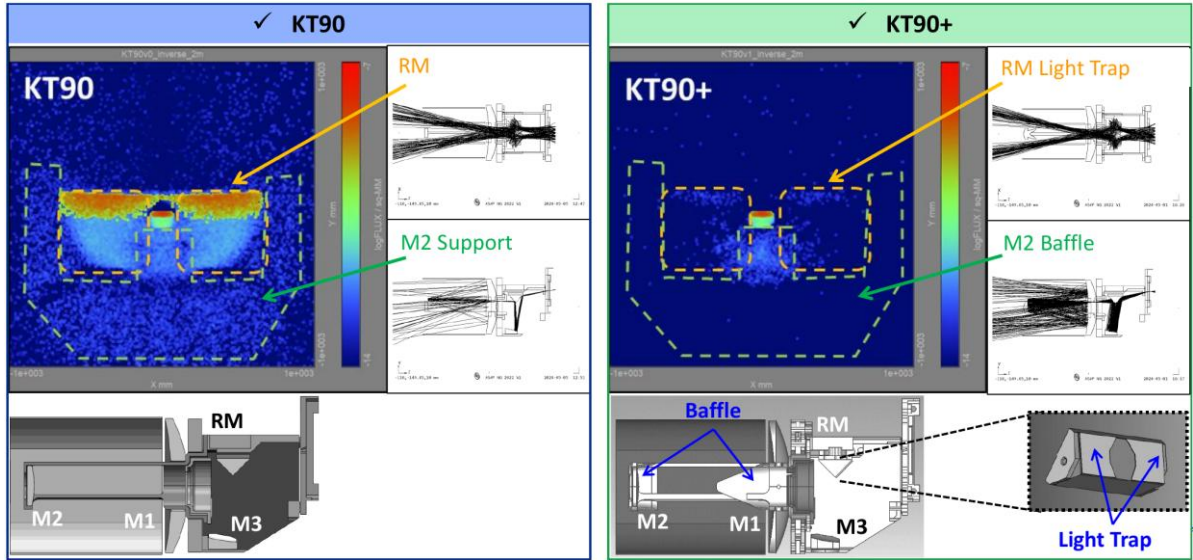


Figure 5. Reverse-ray-tracing comparison of KT90 and KT90+ used to identify stray-light paths and evaluate the added baffles and light traps. The main-path flux is normalized to unity in each model.

Figure 6 summarizes the post-integration reverse-projection inspection. A source placed near the image plane projected the beam onto a screen 2 m from the entrance aperture, and the main spot and surrounding leakage were recorded. Horizontal relative-intensity profiles were normalized to the corresponding main-path samples and used as spatial diagnostics of residual leakage. The HDR-derived profile was also compared with a photometer traverse.

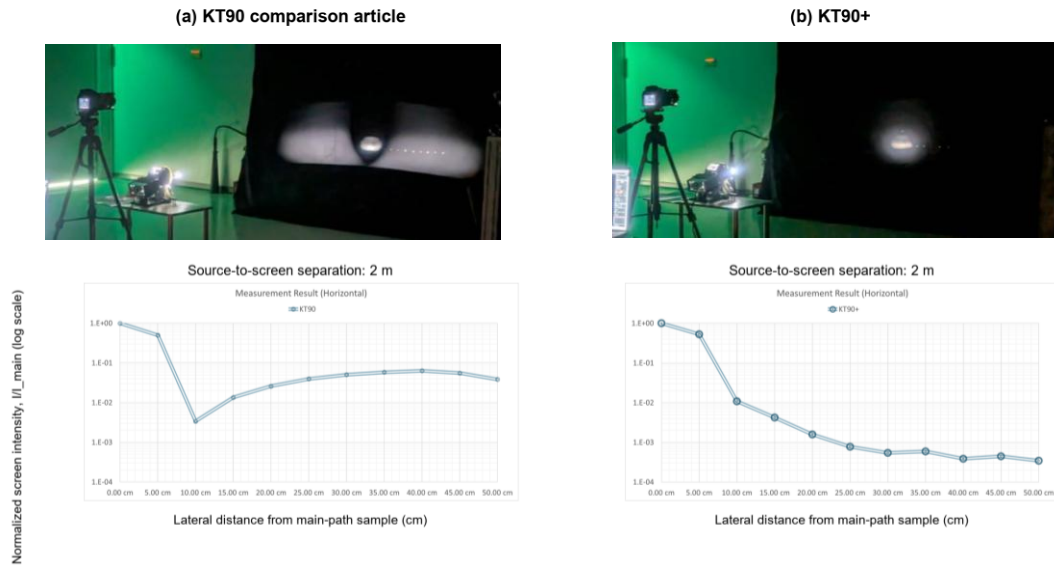


Figure 6. Two-metre reverse-projection screen-test configurations and normalized horizontal relative-intensity profiles for (a) the KT90 comparison article and (b) KT90+.

4. RESULTS

4.1 Coordinate-transfer and wavefront results

CMM assessment and FEA guided selection of the low-deformation magnetic mounting interface. The external target-ball network preserved the common instrument coordinate frame through M1–M2 bonding and the subsequent installation of the M3 and roof-mirror fixtures, providing initial coordinates for full-path interferometric alignment and later FPA placement.

The final 35-term Fringe Zernike fits yielded RMS WFEs of 0.0502, 0.0927, and 0.0902 waves at image-plane field positions $X = 0$, $+5$, and -5 mm, respectively. The RMS WFE was below 0.10 waves at all three sampled positions. Table 1 summarizes the corresponding PV and RMS values.

Table 1. Final 35-term fitted WFE results.

Image-plane field position	PV (waves)	RMS (waves)
$X = 0$ mm	0.3179	0.0502
$X = +5$ mm	0.4094	0.0927
$X = -5$ mm	0.3779	0.0902

4.2 Focal-plane focus selection by CTF

Through-focus CTF served as the focus-selection metric after coordinate transfer. At the selected FPA focus, CTF was 0.12 at 0.93 times the sensor Nyquist frequency.

4.3 Reverse-projection and HDR results

Reverse-ray-tracing simulation predicted that the added baffles and light traps reduced the normalized simulated stray-light flux by more than three orders of magnitude relative to KT90. In the KT90+ hardware reverse-projection test, the relative intensity normalized to the main-path sample was approximately 1×10^{-2} at a lateral distance of 10 cm and decreased to the 10^{-3} – 10^{-4} range over 15–50 cm. The HDR-derived and photometer profiles showed consistent spatial trends, supporting the use of reverse projection to identify residual leakage paths during integration.

5. DISCUSSION

The main value of the KT90+ process is not any single metrology method but the relationship among them. Coordinate transfer places components close enough to the intended geometry that the interferometer can be used without a broad blind search. Interferometry then verifies the optical consequence of the placement and guides the remaining tilt correction before bonding. The retained main-plate targets extend the same coordinate frame to the sensor, while through-focus CTF provides an image-domain focus-selection metric. Reverse projection then checks whether the assembled hardware follows the stray-light paths anticipated by the model. Each layer answers a different question, and no single result is used as a substitute for the others.

The final wavefront and CTF results show how the coordinate-referenced sequence supports optical closure across mirror assembly and focal-plane integration. The target-ball network preserves the common instrument frame between mechanical placement and interferometric verification, while through-focus CTF provides an image-domain focus-selection metric after FPA installation.

The stray-light workflow follows the same design-analysis-build-test logic. Reverse ray tracing identifies paths requiring suppression, and the reverse-projection screen test provides a direct spatial check of the assembled telescope. Together with the HDR and photometer profiles, these measurements connect the modelled baffle and light-trap design to hardware inspection and provide practical feedback for subsequent integration.

6. CONCLUSION

KT90+ demonstrates an integrated assembly and verification workflow for a compact Korsch telescope. CMM-based target-ball coordinate transfer links mirror placement, interferometric alignment, and FPA installation within a common instrument frame. CMM assessment and FEA guided selection of a low-deformation magnetic mounting interface. The final 35-term Fringe Zernike fits yielded RMS WFEs of 0.0502, 0.0927, and 0.0902 waves at image-plane field positions $X = 0, +5$, and -5 mm, respectively. Through-focus CTF served as the FPA focus-selection metric, yielding 0.12 at 0.93 times the sensor Nyquist frequency. Added baffles and light traps reduced the normalized simulated stray-light flux by more than three orders of magnitude relative to KT90, while reverse projection, HDR imaging, and photometer sampling provided a hardware diagnostic of residual leakage. These results demonstrate a traceable process connecting opto-mechanical assembly, image-plane alignment, and stray-light verification in a compact CubeSat telescope.

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