

Correlation-based Shack–Hartmann and double-slit piston metrology for on-orbit alignment of a 3.6-m-class Earth-observing segmented space telescope

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ABSTRACT

Geostationary Earth observation requires a large-aperture optical telescope to achieve high spatial resolution from an altitude of approximately 36,000 km. This paper presents a complementary metrology concept for on-orbit alignment of a 3.6-m-class visible-wavelength Earth-observing telescope with a six-segment primary mirror. The proposed approach combines scene-based correlation-based Shack–Hartmann wavefront sensing and stellar-reference double-slit piston-step sensing within an image-based coarse-to-fine alignment sequence. The Shack–Hartmann sensor uses spatially extended terrestrial scenes as reference objects, enabling single-pass wavefront monitoring during nominal Earth observation. Breadboard experiments demonstrated full-aperture wavefront reconstruction with repeatability better than 0.02λ rms at $\lambda = 633$ nm for the standard Zernike terms up to Z21 and for the reconstructed wavefront. Segment-level validation using a segmented-mirror simulation jig confirmed reconstruction of local wavefronts for individual segment apertures and measurement of relative tilt and focus-related components, with residual standard deviations of 0.049λ rms for Z2, 0.050λ rms for Z3, and 0.014λ rms for Z5, although further improvement is required to meet the initial segment-level relative-tilt target. For inter-segment piston, which cannot be determined from wavefront-slope information alone, a double-slit cross-fringe sensor using stellar illumination was evaluated by simulation. A coarse/fine mask strategy provided a coarse capture range exceeding ± 20 μm and a final piston measurement accuracy of 50 nm or better after two fine-measurement iterations under Arcturus illumination. These results indicate that the two metrology functions can support practical fine alignment and co-phasing of segmented apertures for future geostationary optical missions.

Keywords: segmented-aperture telescopes, geostationary Earth observation, on-orbit alignment, Shack–Hartmann wavefront sensing, piston metrology

1. INTRODUCTION

Geostationary Earth observation is an attractive mission concept for continuous and timely monitoring of specific regions on the Earth. Because a geostationary satellite remains nearly fixed with respect to the ground, it can provide persistent observation capability that is difficult to achieve with low-Earth-orbit platforms. However, the geostationary orbit is located at an altitude of approximately 36,000 km, and this large observation distance directly limits the achievable ground spatial resolution for a given telescope aperture. Therefore, a large-aperture optical telescope is essential for realizing high-resolution Earth imaging from geostationary orbit.

Within the framework of the K Program “OSCAR” (Optical Synthetic-aperture Collaborative Advanced Research), Japan Aerospace Exploration Agency (JAXA), National Astronomical Observatory of Japan (NAOJ), and Mitsubishi Electric Corporation are studying a large geostationary optical telescope for high-resolution Earth observation. In the present mission concept, a 3.6-m-class telescope with a six-segment primary mirror is considered [1, 2]. A segmented primary mirror is a practical approach for realizing such a large aperture under constraints on manufacturability, mass, structural stability, and launch vehicle accommodation [2]. However, unlike a monolithic mirror, a segmented primary mirror introduces additional alignment degrees of freedom among the mirror segments. Therefore, on-orbit metrology and adjustment are required to maintain the optical performance after launch and during operation [3].

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The optical performance of a segmented telescope is affected by both full-aperture and sub-aperture wavefront-error components. Segment-to-segment errors, including relative tip, tilt, and inter-segment piston, directly degrade the synthesized aperture. Segment-level figure errors, such as curvature errors, also affect the wavefront quality of each sub-aperture. In addition, telescope-level alignment errors, such as axial despace and rigid-body displacement of optical components, generate low-order aberrations including focus error. For the 3.6-m, six-segment geostationary Earth-observing telescope, previous conceptual studies indicated that segment-level errors, including inter-segment piston and segment curvature-radius errors, can significantly affect the synthesized-aperture performance when high-resolution visible-wavelength imaging is targeted [4]. These error sources indicate that complementary sensing functions are necessary for both segment-level alignment and full-aperture optical alignment.

The James Webb Space Telescope has demonstrated on-orbit phasing of a segmented-aperture space telescope. However, the target system in this study differs significantly from JWST in terms of orbit, wavelength region, and observation target. JWST operates around the Sun–Earth L2 point and is designed mainly for infrared astronomical observations. In contrast, the telescope considered here is a visible-wavelength Earth-observing telescope in geostationary orbit. A geostationary Earth-observing satellite experiences time-varying thermal conditions because the relative geometry among the Sun, Earth, and spacecraft changes continuously. Previous thermal-structural-optical analyses showed that, under the assumed thermal-control and low-expansion material conditions, mirror surface deformation can be suppressed to approximately 0.02λ rms, where $\lambda = 633$ nm is used as the reference wavelength throughout this paper, whereas rigid-body displacement of optical components can generate wavefront errors on the order of several wavelengths [4]. This difference in error scale suggests that active on-orbit alignment, including focus-related adjustment and segment-level correction, is essential.

In this study, two metrology functions are considered for the segmented telescope: wavefront sensing for low-order aberrations and relative segment tilts, and piston-step sensing for inter-segment piston measurement. For wavefront sensing, spatially extended terrestrial scenes available during nominal Earth observation are used as reference objects for a single-pass correlation-based Shack–Hartmann wavefront sensor [5, 6, 7]. In contrast, because inter-segment piston steps cannot be determined from Shack–Hartmann wavefront-slope information alone, a stellar-reference double-slit piston sensor is introduced as a dedicated calibration function for segment co-phasing [8]. These two metrology functions are complementary in the assumed on-orbit alignment scenario.

This paper presents a metrology concept and feasibility assessment for on-orbit alignment of a 3.6-m-class geostationary segmented Earth-observing telescope. Section 2 summarizes the metrology concept for the assumed on-orbit alignment framework. Section 3 describes the principle and breadboard validation of the correlation-based Shack–Hartmann wavefront sensor using extended terrestrial scenes. Section 4 discusses its application to segment-level relative tilt and focus-related alignment. Section 5 presents the piston-step metrology concept for segment co-phasing under stellar reference illumination. Finally, Section 6 summarizes the integrated metrology scenario, key feasibility results, and remaining technical issues toward future validation.

2. METROLOGY CONCEPT FOR ON-ORBIT ALIGNMENT

In a large-aperture telescope using a segmented primary mirror, it is difficult to achieve near-diffraction-limited imaging performance in the visible wavelength range only by mechanically placing each mirror segment at its nominal position. Launch vibration, thermal deformation, and reaction forces from the mirror support structures can generate wavefront errors, including relative segment tilt and inter-segment piston. Therefore, an on-orbit metrology concept is required to guide the adjustment of the segmented optical system as a synthesized aperture.

For the geostationary segmented Earth-observing telescope considered in this study, wavefront errors are classified into full-aperture and sub-aperture components [3]. Full-aperture aberrations are low-order aberrations of the entire telescope, such as defocus and astigmatism, and are mainly corrected by telescope-level adjustment mechanisms, including secondary-mirror adjustment. Sub-aperture aberrations originate from individual primary mirror segments and include relative segment tilt, inter-segment piston, and segment-level wavefront errors such as curvature-related components. These errors must be evaluated and corrected by segment-level adjustment mechanisms. Accordingly, the alignment framework requires complementary image-based, wavefront-based, and piston-step-based metrics.

For the feasibility assessment in this paper, the metrology targets are defined as follows. The full-aperture wavefront-error goal is assumed to be 0.02λ rms at the reference wavelength of $\lambda = 633$ nm, consistent with the optical-system-level wavefront-error goal considered for the geostationary optical satellite. For segment-level relative-tilt measurement, an initial target accuracy of 0.007λ rms is used. Throughout this paper, wavefront-error values are defined assuming single-

pass measurements. For piston-step measurement, the final measurement accuracy target is set to 50 nm or better, while the coarse piston sensor is required to provide a capture range large enough to cover the residual piston error after the preceding image-based and wavefront-based alignment steps. In the present feasibility assessment, a coarse capture range of at least $\pm 20\ \mu\text{m}$ is considered. These values are used as provisional targets in the present feasibility assessment and should be updated consistently with the final alignment error budget.

Figure 1 shows the conceptual flow of the assumed on-orbit alignment procedure [4, 9]. Table 1 also summarizes the assumed alignment steps and their corresponding metrology metrics. In the initial stage, focal-plane images are used for coarse alignment. Image metrics are used for initial focus adjustment, identification of the correspondence between each mirror segment and each focal-plane image, confirmation of segment response and crosstalk, coarse focus adjustment, and geometrical superposition of the segment images. This image-based stage brings the telescope into a condition where wavefront and piston-step measurements can be effectively applied.

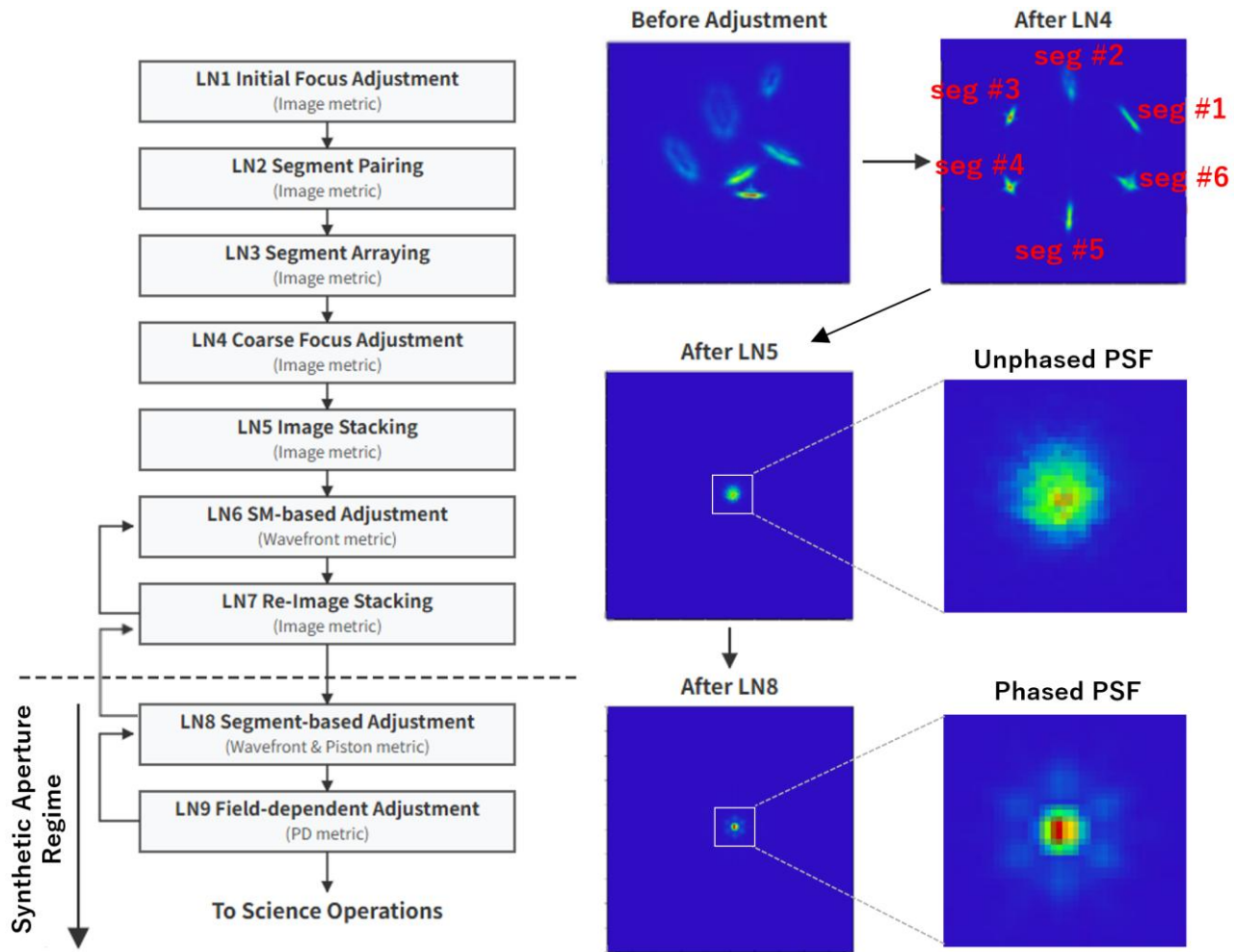


Figure 1. Conceptual flow of the on-orbit alignment procedure for the segmented telescope.

After image-based coarse alignment, wavefront-based adjustment is performed. In this stage, wavefront information over the full aperture is used for secondary-mirror-based adjustment to reduce low-order aberrations. Local wavefront information associated with each segment is also used to evaluate relative segment tilt and focus-related segment errors. In this paper, this function is mainly provided by a correlation-based Shack–Hartmann wavefront sensor using extended terrestrial scenes, as described in Sections 3 and 4.

Inter-segment piston steps cannot be determined only from Shack–Hartmann wavefront slope information. Therefore, a dedicated piston-step metrology method is required for segment co-phasing. In this study, a double-slit cross-fringe piston sensor under stellar reference illumination is considered for this purpose. The sensor estimates piston steps from interference-fringe displacement generated by light passing through selected segment apertures. The piston-sensing concept is described in Section 5. If required, a field-dependent adjustment step can also be added after the center-field optical performance is optimized. In this optional step, image-based wavefront estimation using Phase Diversity [10] is used to evaluate field-dependent aberrations at multiple field positions and to further optimize the telescope alignment over the observation field.

Table 1. Assumed on-orbit alignment steps and corresponding metrology metrics

Step	Alignment item	Main metric	Description
LN1	Initial focus adjustment	Image	Adjust the focus position from the spread of the PSF.
LN2	Segment-image pairing	Image	Identify the correspondence between each mirror segment and each focal-plane spot image.
LN3	Alignment confirmation	Image	Tilt each segment individually and confirm image response and crosstalk.
LN4	Coarse focus adjustment	Image	Evaluate the PSF FWHM and correct coarse defocus.
LN5	Geometrical superposition	Image	Superpose the spot images from individual segments at the specified focal-plane position.
LN6	Secondary-mirror-based adjustment	<u>Wavefront</u>	Reduce low-order aberrations by translating and tilting the secondary mirror.
LN7	Re-geometrical superposition	Image	Correct spot displacement generated after secondary-mirror adjustment.
LN8	Segment-based adjustment	<u>Wavefront/ Piston step</u>	Correct relative segment tilt and inter-segment piston steps.
LN9	Field-dependent adjustment	Phase Diversity	Evaluate field-dependent aberrations using image-based wavefront estimation.

The metrology concept discussed in this paper is organized according to this alignment procedure. Image metrics provide robust coarse alignment over a relatively large misalignment range. The correlation-based Shack–Hartmann wavefront sensor provides wavefront information for secondary-mirror adjustment and segment-level relative-tilt correction. The double-slit cross-fringe piston sensor provides piston-step information required for co-phasing the segmented aperture. By combining these complementary metrics, the proposed metrology concept aims to support practical on-orbit alignment of a visible-wavelength geostationary segmented Earth-observing telescope.

3. CORRELATION-BASED SHACK–HARTMANN WAVEFRONT SENSOR

Among several wavefront-sensing methods, the Shack–Hartmann approach was selected as the baseline wavefront sensor. Shack–Hartmann sensors, curvature sensors, and pyramid sensors were considered as candidate methods. The Shack–Hartmann approach has advantages in terms of wide dynamic range, high measurement rate, compact and lightweight optical configuration, relatively small computational load, and robustness. These characteristics are particularly important for a satellite-borne wavefront sensor. The wide dynamic range is useful because segment-level tilt components must be detected in a segmented-aperture telescope. In addition, the Shack–Hartmann sensor can be configured with a static optical system based on a microlens array and an image sensor, which is advantageous for maintaining robustness under the spacecraft environment.

The present study adopts a single-pass wavefront-sensing configuration. One possible single-pass approach is to use stellar objects as point-source references, but this requires dedicated stellar calibration opportunities and can cause observation loss for a geostationary Earth-observing mission. In contrast, the correlation-based Shack–Hartmann sensor uses terrestrial scenes that are being observed by the telescope, enabling wavefront sensing during Earth observation without relying solely on stellar calibration observations [5, 6, 7]. This scene-based capability is also useful for monitoring wavefront variations under the actual observing thermal conditions, because the thermal environment of a geostationary satellite changes with the Sun–Earth–spacecraft geometry as mentioned in Section 1.

Figure 2 shows the laboratory setup used for breadboard validation of the satellite-borne correlation-based Shack–Hartmann wavefront sensor. The setup simulates single-pass wavefront sensing with extended terrestrial scenes and consists of an illumination source, a ground-image film, optics simulating the satellite optical system, and the wavefront sensor breadboard model (BBM). Because the breadboard sensor includes refractive optics and a wavelength selection filter, a red LED source was used instead of a broadband white-light source. Ground-image films, including resolution charts and simulated terrestrial scenes, were used as reference objects.

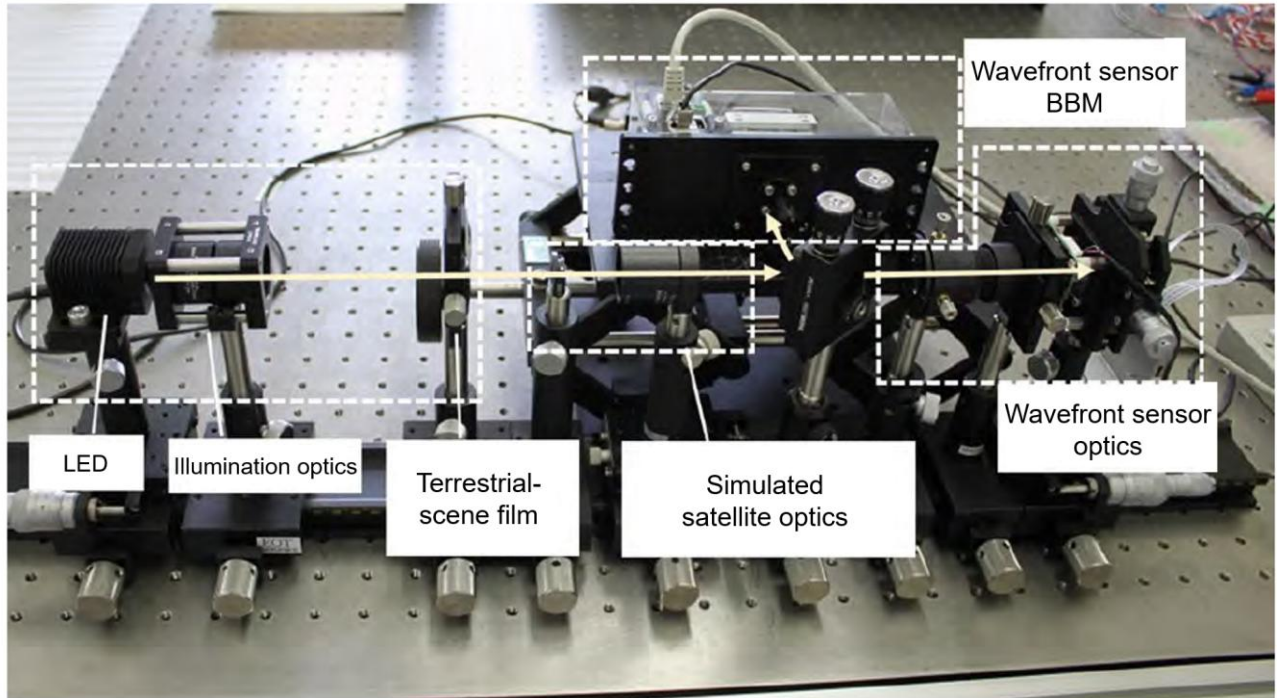


Figure 2. Laboratory setup for breadboard validation of the satellite-borne correlation-based Shack–Hartmann wavefront sensor using terrestrial scenes.

In the present sensor, the sub-aperture signals are not isolated point-source spots but images of an extended terrestrial scene. Therefore, the displacement of each sub-aperture image is estimated by template matching based on image correlation. A sub-aperture image is selected as a reference template, and the relative positions of the other sub-aperture images are estimated from the peak or centroid position of the cross-correlation function. The BBM used a CMOS image sensor with 1024×1280 pixels and a pixel pitch of $5.3 \mu\text{m}$. The frame rate of the image sensor was 60 fps, while the assumed wavefront measurement rate was 10 fps. Figure 3 shows an example terrestrial scene, the acquired Hartmann image, and the reconstructed wavefront error map obtained with the correlation-based Shack–Hartmann wavefront sensor BBM. The breadboard evaluation confirmed that the sensor can perform single-pass wavefront sensing using external terrestrial scenes. For the full pupil, the standard Zernike coefficients from Z4 to Z21 were obtained. The repeatability was evaluated by measuring the same optical system using different regions of terrestrial scenes. The obtained repeatability was less than 0.02λ rms for each Zernike term up to Z21 and less than 0.02λ rms for the reconstructed wavefront.

The measurement accuracy of the correlation-based sensor depends on the spatial structure, contrast, and spectral characteristics of the terrestrial scene used as the reference object. This dependence arises because the displacement of each sub-aperture image is estimated from the correlation function of extended-scene images. Therefore, the width and shape of the cross-correlation function are useful intermediate indicators for evaluating whether a terrestrial scene is suitable for wavefront sensing. Several types of terrestrial scenes were evaluated. A resolution chart and residential or urban scenes produced narrow cross-correlation functions and were suitable for displacement estimation. A scene containing gas tanks produced a main correlation peak together with sub-peaks due to its periodic structure. Such sub-peaks must be properly handled to avoid false displacement estimation. Scenes containing large structures comparable to the sensor field of view produced broad cross-correlation functions and degraded the displacement accuracy. In addition, because the breadboard sensor used a red wavelength selection filter, scenes whose features were weakened by spectral filtering produced anisotropic or broad correlation functions. These results indicate that extended terrestrial scenes can be used as external reference objects for single-pass Shack–Hartmann wavefront sensing, while suitable scene selection is necessary for robust displacement estimation.

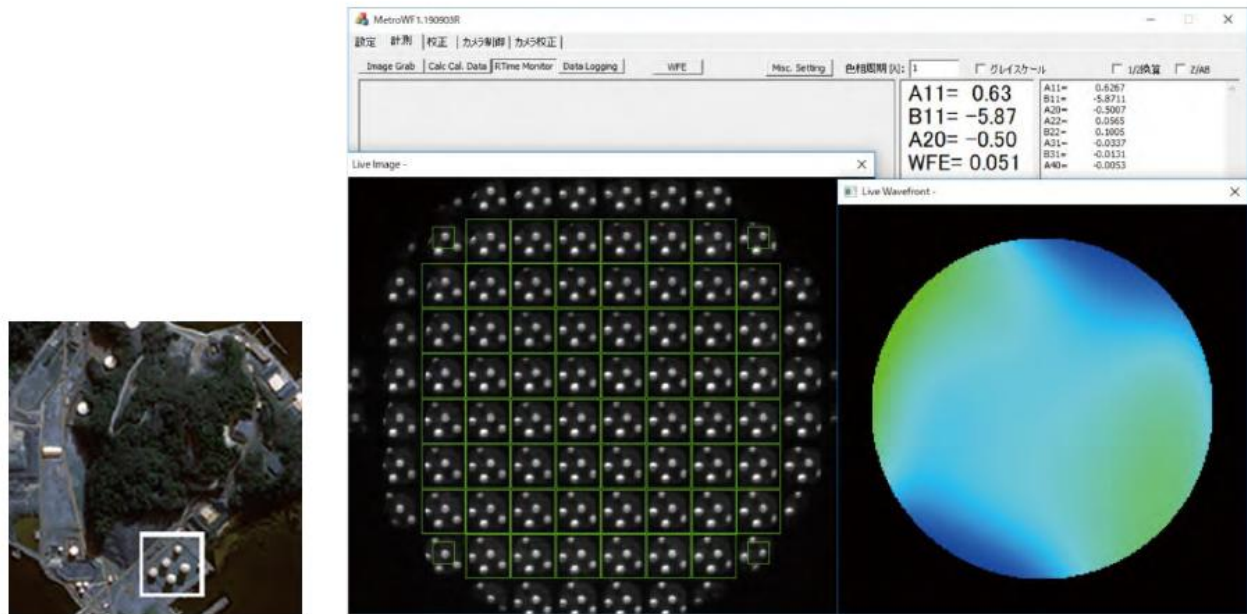


Figure 3. Example measurement obtained with the correlation-based Shack–Hartmann wavefront sensor BBM, including the terrestrial scene, acquired Hartmann image, and reconstructed wavefront error map.

4. APPLICATION TO SEGMENTED-APERTURE ALIGNMENT

The correlation-based Shack–Hartmann wavefront sensor described in Sect. 3 was evaluated for segment-level wavefront sensing. In a segmented-aperture telescope, full-aperture wavefront information alone is not sufficient for on-orbit alignment. Local wavefront errors for each mirror segment must also be measured to correct relative segment tilt and focus-related errors. Therefore, a laboratory validation test was conducted using the wavefront sensor BBM and a segmented-mirror simulation jig.

The validation focused on the standard Zernike coefficients of the relative tilt components Z2 and Z3 and the focus-related component Z5. These components are directly related to segment-level adjustment of a segmented primary mirror. Figure 4 shows the laboratory setup for the segment-level validation test. The simulation jig consisted of two off-axis parabolic mirrors representing two primary-mirror segments and one secondary mirror. It was combined with the wavefront sensor BBM and an LED-illuminated ground-image film to reproduce the single-pass terrestrial-scene measurement condition assumed for on-orbit operation.

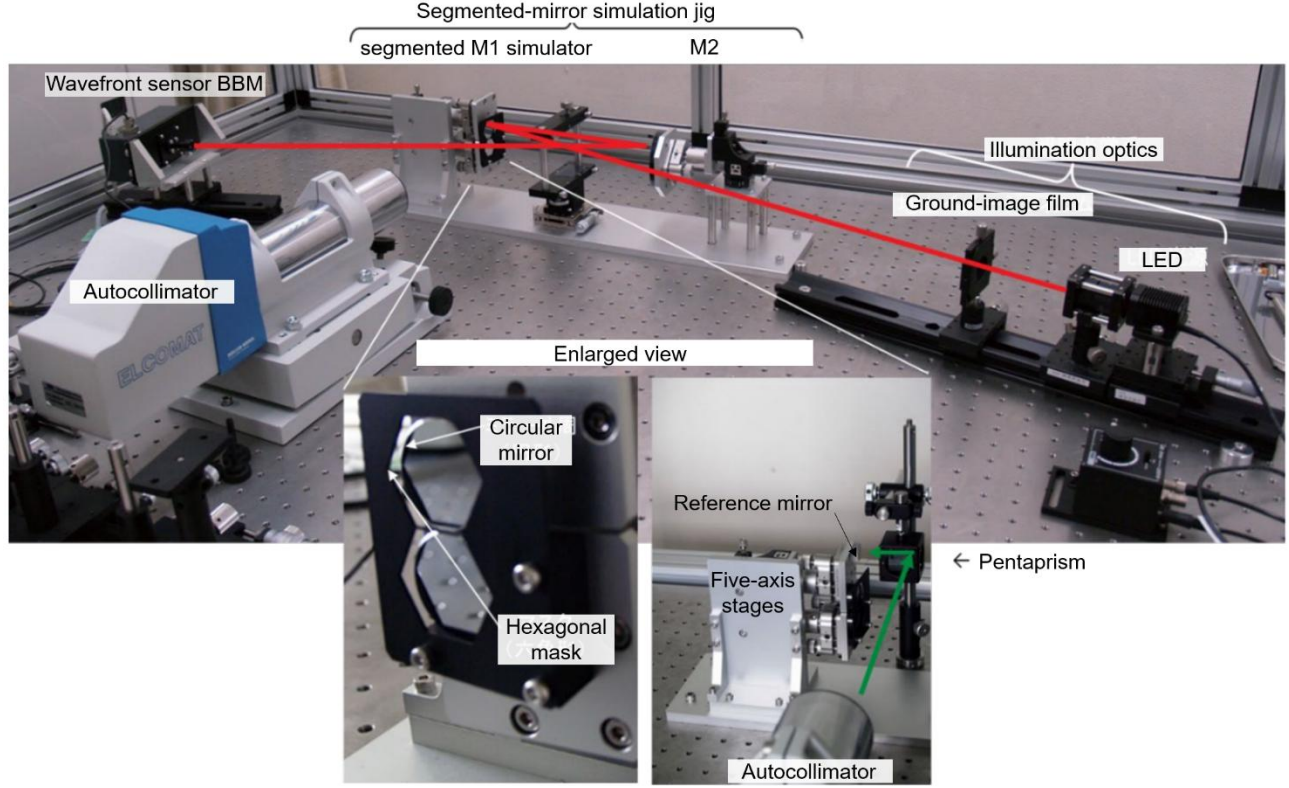


Figure 4. Laboratory setup for segment-level validation using the segmented-mirror simulation jig and the correlation-based Shack–Hartmann wavefront sensor BBM.

Figure 5 shows the acquired Hartmann image and reconstructed local wavefronts obtained with the setup shown in Fig. 4. The two simulated segment apertures were aligned within the microlens-array field of the wavefront sensor. Each segment aperture included at least a 3×3 arrangement of microlenses. The outer edges of adjacent segment apertures were intentionally placed within the same microlens row to evaluate the influence of segment-edge regions. A ground-image film of an urban or residential area was used as the reference scene because such scenes provide narrow cross-correlation functions and are suitable for displacement estimation, as mentioned in Sect. 3. The segment edges were not masked in the initial test. Even under this condition, the relative positions of the sub-aperture images were obtained from the peak or centroid positions of the cross-correlation functions. From the measured Hartmann images, local wavefronts for the two segment apertures were reconstructed and expanded into the standard Zernike coefficients. The experiment confirmed that the standard Zernike coefficients from Z2 to Z10 could be obtained for each segment aperture. This result confirms the functional capability required for measuring the target segment-level components, including Z2, Z3, and Z5.

Quantitative accuracy tests were then performed for relative tilt and focus. For the relative tilt measurement, one simulated segment mirror was tilted using the adjustment mechanism of the jig. Because the mechanical adjustment resolution was not sufficient for small angular steps, an autocollimator was used to monitor the actual mirror tilt. For Z2, lateral tilt was applied to one simulated segment mirror. The difference in the Z2 coefficient between the upper and lower segment apertures was calculated from the reconstructed local wavefronts. More than 10 measurement points were obtained while changing the tilt in one direction to avoid backlash. The applied relative tilt was approximately 5λ rms. The measured Z2 difference showed linear behavior with respect to the autocollimator reading, and the standard deviation of the residual from the linear fit was 0.049λ rms. The same procedure was applied to Z3. The applied relative tilt was approximately 4λ rms, and more than 10 measurement points were obtained. The standard deviation of the residual from the linear fit was 0.050λ rms. No significant difference was observed between the Z2 and Z3 results. For Z5, one simulated segment mirror was translated along the optical-axis direction to introduce defocus. The difference in the Z5 coefficient between the two segment apertures was calculated while driving the micrometer in one direction. The measured Z5 difference showed

linear behavior with respect to the micrometer displacement, and the standard deviation of the residual from the linear fit was 0.014λ rms.

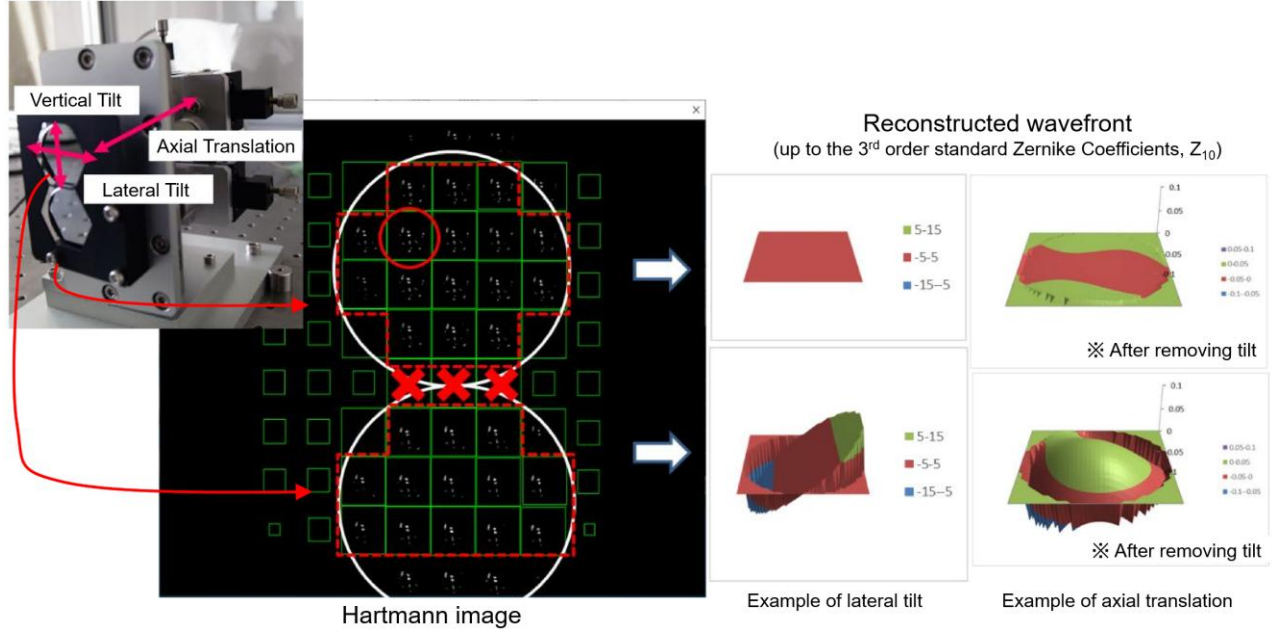


Figure 5. Acquired Hartmann image and reconstructed local wavefronts for the two simulated segment apertures.

These results demonstrate that the correlation-based Shack–Hartmann wavefront sensor can extract local wavefronts for individual segment apertures and detect segment-level relative tilt and focus-related components using extended-scene illumination. However, the demonstrated relative-tilt accuracy of approximately 0.05λ rms does not satisfy the initial segment-level target of 0.007λ rms defined in Sect. 2. Further improvement is therefore required to meet the target accuracy for segment-level alignment.

The expected improvement for a geostationary application was estimated from two factors. The first factor is the increase in the number of sub-apertures per segment. In the BBM test, the number of sub-apertures per segment was approximately 13 to 16. For the geostationary optical satellite configuration, adding one ring of sub-apertures in the assumed honeycomb arrangement increases the effective number of sub-apertures and gives an expected improvement factor of approximately 1.49 considering the spider shadows. The second factor is the reduction of the effective reference-source size. In the correlation-based method, this size corresponds to the width of the cross-correlation function. Scenes with fine structures, such as residential or urban areas, produce narrow correlation functions, whereas large low-spatial-frequency structures and periodic patterns degrade displacement estimation. Based on the comparison between point-source and extended-source cases, selecting finer reference structures is expected to improve the wavefront measurement error by approximately a factor of 2. By applying these two improvement factors to the demonstrated relative-tilt accuracy, the expected accuracy is estimated to be 0.017λ rms. This estimated value still does not satisfy the initial segment-level target of 0.007λ rms. However, it is comparable to the optical-system-level wavefront-error goal of 0.02λ rms considered for the geostationary optical satellite. Therefore, the correlation-based Shack–Hartmann wavefront sensor is expected to be useful for reducing relative segment tilt and focus-related errors to a level compatible with the overall wavefront-error budget, provided that the sensor design, optical sensitivity correction, reference-scene selection, and image-correlation algorithm are optimized together.

5. DOUBLE-SLIT PISTON-STEP METROLOGY FOR SEGMENT CO-PHASING

As discussed in Sect. 2, inter-segment piston steps cannot be determined only from Shack–Hartmann wavefront-slope information. In this study, we introduced a double-slit cross-fringe piston sensor using stellar reference illumination [8],

and evaluated the feasibility of the method in terms of the measurable mirror-step range and the final measurement accuracy required for segment co-phasing. Figure 6 shows the concept of the double-slit piston-step sensor and the adopted coarse/fine mask configurations. A double-slit mask is placed at a pupil plane conjugate to the primary mirror. For each segment boundary to be measured, a pair of slits is arranged so that each slit corresponds to one of the two adjacent mirror segments. When one segment is axially displaced relative to the adjacent segment, an optical path difference is introduced between the wavefronts transmitted through the two slits. This optical path difference appears as a displacement of the interference-fringe pattern on the detector. Therefore, the inter-segment mirror step, corresponding to the segment piston displacement, can be estimated from the measured fringe displacement.

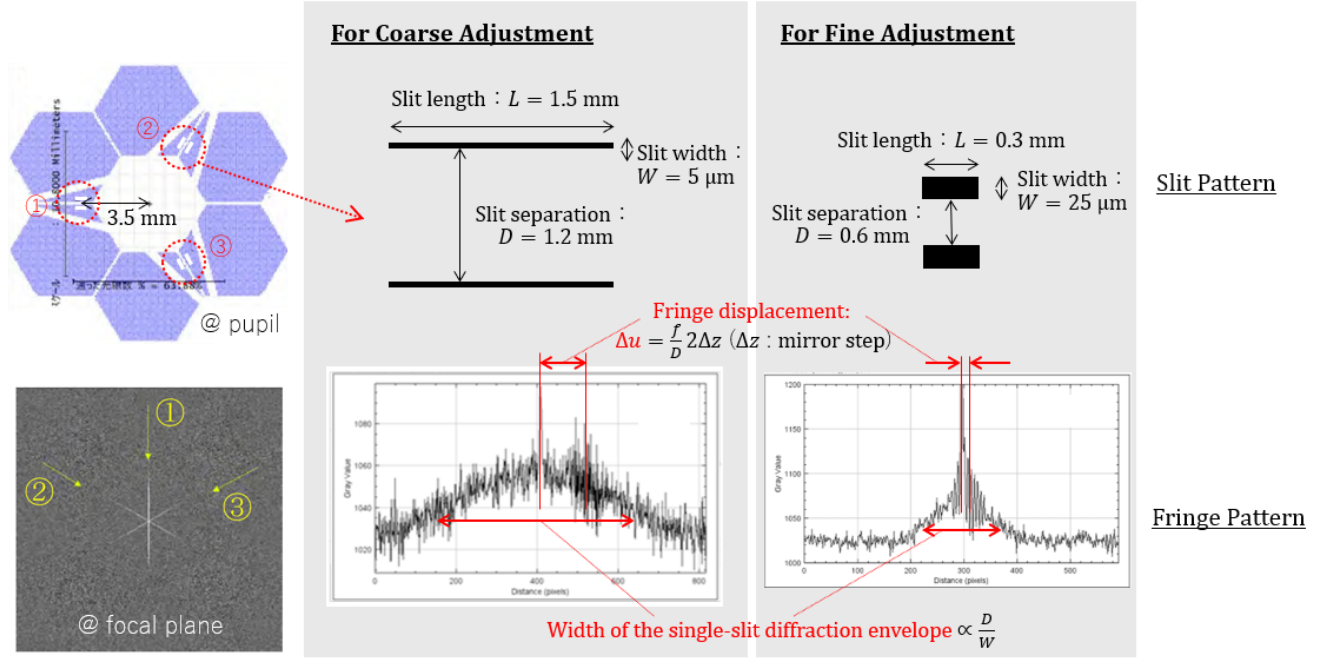


Figure 6. Concept of the double-slit piston-step sensor and adopted coarse/fine mask configurations.

The parameters of the double-slit mask were selected by considering the relationship between mirror step, fringe displacement, measurable range, photon flux, and detector sampling. The fringe displacement Δu caused by a mirror step Δz is expressed as

$$\Delta u = f \cdot 2\Delta z / D,$$

where f is the focal length of the downstream imaging optics and D is the slit separation. The factor of 2 accounts for the optical path difference introduced by reflection. The measurable range R is limited by the width of the single-slit diffraction envelope, as illustrated in Fig. 6, and was evaluated as

$$R = 0.6 \cdot D\lambda_0 / 2W,$$

where W is the slit width and λ_0 is the center wavelength. These relations indicate the basic trade-offs in the double-slit mask design. For example, a larger D increases the measurable range, but it decreases the fringe displacement per unit mirror step and shortens the fringe period on the detector, making detector sampling and accurate fringe analysis more difficult.

Based on the trade-offs, a two-step measurement strategy was adopted. The coarse mask was designed to provide a wide measurable range for large initial mirror steps, whereas the fine mask was designed to provide higher-accuracy estimation after the residual mirror step had been reduced. The slit parameters were selected in the following order to satisfy the measurement range and accuracy targets defined in Sect. 2. First, the slit separation D was selected according to the role

of each mask, considering the measurable range, fringe displacement sensitivity, and detector sampling. Second, the slit length L was determined to avoid spider or truss shadows and segment-edge regions, while maintaining separability of the fringe components in spatial-frequency space. Finally, the slit width W was selected by considering the measurable range, photon flux, and the resulting signal-to-noise ratio of the fringe profile used for fringe analysis.

Table 2 summarizes the adopted coarse and fine mask parameters and the expected mirror-step measurement performance. For coarse measurement, the adopted mask uses $W = 5\text{ }\mu\text{m}$, $L = 1.5\text{ mm}$, and $D = 1.2\text{ mm}$ on the 20-mm-diameter pupil mask, providing a measurable range larger than $20\text{ }\mu\text{m}$. For fine measurement, the adopted mask uses $W = 25\text{ }\mu\text{m}$, $L = 0.3\text{ mm}$, and $D = 0.6\text{ mm}$ on the same mask plane. The calculated measurable range of the fine mask is $\pm 3.6\text{ }\mu\text{m}$. Because each mask measures three segment boundaries simultaneously, two mask positions are used to cover the six inter-segment boundaries of the six-segment primary mirror. The total number of masks is four, corresponding to two mask types and two boundary groups.

Table 2. Adopted double-slit mask parameters and mirror-step measurement performance.

Purpose	Slit width W	Slit length L	Slit separation D	Performance
Coarse	$5\text{ }\mu\text{m}$	1.5 mm	1.2 mm	Measurable range: $>20\text{ }\mu\text{m}$; accuracy: $\pm 1.5\text{ }\mu\text{m}$
Fine	$25\text{ }\mu\text{m}$	0.3 mm	0.6 mm	Measurable range: $\pm 3.6\text{ }\mu\text{m}$; accuracy: $\leq 50\text{ nm}$ after two fine-measurement iterations

The expected performance was evaluated using simulated fringe images under stellar reference illumination by wavefront propagation using Fourier-based methods. The assumed reference source was Arcturus, with an apparent magnitude of -0.04 . The piston-step sensor was assumed to use a wavelength range of $475\text{--}565\text{ nm}$, whereas the wavefront sensor was assumed to use a separate wavelength range of $565\text{--}690\text{ nm}$. The standard exposure time was set to 0.1 s based on the pointing-stability constraint. The detector was assumed to have 2048×2048 pixels with a pixel pitch of $10\text{ }\mu\text{m}$. Noise was added to the simulated fringe images by considering readout noise, shot noise, and visible background light. The readout noise was assumed to be $4\text{ e}^-/\text{pixel}$, the dark current was neglected because of the short exposure time, and the visible background level was assumed to be equivalent to $1/1000$ of the Arcturus signal.

The fringe images were processed before mirror-step estimation. Spatial-frequency filtering was first applied to isolate the fringe component corresponding to a selected segment boundary and to remove unrelated high-frequency components. The extracted fringe image was then rotated so that the fringe direction became parallel to the detector columns. A one-dimensional fringe profile was obtained from the column with the maximum fringe amplitude. For fine measurement, the mirror step was estimated by fitting a polychromatic double-slit fringe model to this one-dimensional profile.

In the coarse-measurement evaluation, the adopted coarse mask provided a measurable mirror-step range larger than $20\text{ }\mu\text{m}$ with an estimation accuracy of about $\pm 1.5\text{ }\mu\text{m}$. This accuracy is sufficient to bring the residual mirror step into the measurable range of the fine mask. In the fine-measurement evaluation using Arcturus, residual mirror steps of 0 and $0.5\text{ }\mu\text{m}$ satisfied the 50-nm accuracy requirement. For an initial residual mirror step of $2\text{ }\mu\text{m}$, some cases did not satisfy the 50-nm requirement in a single fine measurement. However, the results indicate that two fine-measurement iterations can reduce the mirror-step error to 50 nm or less. Therefore, the combination of coarse and fine masks is expected to satisfy the piston-step metrology targets defined in Sect. 2: a coarse capture range of at least $\pm 20\text{ }\mu\text{m}$ and a final measurement accuracy of 50 nm or better under bright stellar reference illumination.

6. DISCUSSION AND CONCLUSION

This paper presented complementary metrology functions for on-orbit alignment of a 3.6-m-class geostationary segmented Earth-observing telescope: scene-based correlation-based Shack–Hartmann wavefront sensing for low-order aberrations and relative segment tilt, and stellar-reference double-slit piston-step sensing for inter-segment piston measurement. In the assumed alignment scenario, image-based coarse alignment is first performed, followed by wavefront-based and piston-step-based metrology for fine alignment of the segmented aperture.

Breadboard validation showed that the correlation-based Shack–Hartmann wavefront sensor can perform single-pass wavefront sensing using spatially extended terrestrial scenes. For the full pupil, the repeatability was less than 0.02λ rms for each Zernike term up to Z21 and also less than 0.02λ rms for the reconstructed wavefront. Segment-level validation further demonstrated that local wavefronts can be reconstructed for individual segment apertures. The residual standard deviations from linear fits were 0.049λ rms for Z2, 0.050λ rms for Z3, and 0.014λ rms for Z5. Although the demonstrated relative-tilt accuracy does not yet satisfy the initial segment-level target of 0.007λ rms, the expected accuracy for the geostationary application is estimated to be 0.017λ rms by increasing the number of sub-apertures and selecting finer reference-scene structures. This value is comparable to the optical-system-level wavefront-error goal of 0.02λ rms.

For piston-step metrology, simulations under Arcturus illumination showed that the adopted coarse/fine double-slit mask strategy can provide the required coarse capture range and achieve a final measurement accuracy of 50 nm or better after two fine-measurement iterations. These results indicate that the two metrology functions are complementary: the scene-based Shack–Hartmann sensor enables frequent wavefront and relative-tilt monitoring during nominal Earth observation, whereas the stellar-reference double-slit sensor provides the piston information required for segment co-phasing during dedicated calibration opportunities.

Future work includes optimization of the wavefront sensor design, calibration of optical sensitivity, robust selection of suitable terrestrial scenes, improvement of the image-correlation algorithm, hardware validation of the piston sensor under representative photon-flux, pointing-stability, and background-light conditions, and system-level verification of the integrated alignment procedure.

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