Slanted-edge MTF focus test verification with PRF testing to establish best focus position of infinite conjugate space optical systems

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ABSTRACT

For earth-viewing, fixed-focus, space optical systems, carefully finding the best focus position of the instrument is critical to achieving the best possible image performance and mission success. For such space optical systems, modulation transfer function (MTF) test data is directly applicable to system optical resolution. Furthermore, MTF test products can be combined to predict overall imaging performance. The infinite conjugate slanted-edge MTF test can be used in ground testing to identify best focus of the optical system while taking into account the entire imaging system, operational parameters, and simulated operational environment. The point-response function (PRF) test can be used to verify the results of the slanted-edge MTF test to ensure that the optimum best focus position is determined. This paper discusses the slanted-edge MTF test for establishing best focus and the PRF test for verifying the best focus. Actual MTF and PRF test results are presented.

Keywords: MTF, PRF, focus, slanted edge, space telescope, optical test, alignment, verification

1. INTRODUCTION

A fixed-focus space optical system relies on a confidently determined best focus position to acquire high-quality images and enable mission success. For an optical telescope assembly (OTA) unit under test (UUT), the slanted-edge MTF focus test is used as the primary method to find the best focus, and the PRF test is used to verify this best focus, increase confidence in the result, and identify any issues that should be investigated. In this paper, both the MTF and PRF tests are conducted on-axis only.

It should be noted that gravity effects must be included in the data acquisition and processing in order to simulate zero-G conditions. There are existing gravity mitigation techniques to enable slanted-edge MTF focus testing to provide data relevant for zero-G conditions[1]. For the purposes of this paper, gravity effects are not initially considered, rather, only one gravity orientation is tested for both the slanted-edge MTF test and the PRF test as a first step towards verification of focus position.

This paper discusses the verification of the slanted-edge MTF test with the PRF test for an OTA UUT. This OTA has significant gravity-induced astigmatism and a non-monochrome focal plane array (FPA), presenting unique challenges. First, the MTF and PRF methods are summarized.

2. DISCUSSION OF METHODS

2.1 Method introduction

There are several different methods used to define imaging performance for an optical system, and the choice of what method to use is largely dependent on the testing objectives. Wavefront error (WFE) is commonly used in testing individual optical components, mostly due to WFE tests being achieved through interferometry. PRF tests are used to characterize aberration throughout an optical system when viewing a point source. Space Dynamics Laboratory (SDL) has heritage performing PRF tests for focal plane alignment, including SPIRIT III[2]. The MTF is commonly used to test the imaging quality of optical systems with digital focal plane arrays. The MTF test has the advantage of being multiplicative in nature, which enables the MTF results of subsystems to be combined to determine overall optical performance. Both the MTF test and PRF test allow for the entire UUT, including the detector and the various optical components, to be characterized under operating conditions, strongly supporting the use of the MTF test and PRF test to define imaging performance for this effort.

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2.2 Slanted-edge MTF measurement method

The slanted-edge MTF measurement has been adopted as a standardized method for measuring optical performance by the international community. The international standard ISO 12233 was used as a baseline for the MTF measurement to keep with industry standards[3]. However, several adaptations were necessary to facilitate measuring an earth-viewing space telescope at infinite conjugate. The adaptations and methods used for the slanted-edge MTF test have been described in another paper[1]. The test is briefly discussed here for the sake of clarity. A precision mechanical edge was back-illuminated by an integrating sphere and collimated by a large reflective optic. This was then folded in collimated space and presented to the entrance pupil of the UUT. The objective was to produce an image of the slanted edge at different field angles on the unit under test's focal plane. The best focus position for both defocus and tip/tilt of the focal plane could be found by analysis of the MTF for the slanted edge at different field angles by using a defined region of interest. The slanted-edge MTF test can be performed in orbit to verify pre-launch testing using man-made objects such as roads, airport runways, and other objects that facilitate straight and high-contrast imagery[4].

2.3 PRF test

The PRF quantifies the optical system's response to a point source input and describes how the point source disperses spatially about the optical axis. The PRF is commonly used in astronomical optics because the characterization of a point source, e.g., a star, is often important in such an application. However, the PRF, combined with different figures of merit (e.g., encircled energy, ensquared energy, FWHM) is used in the alignment of various optical systems to accomplish accurate positioning of the focal plane array[5].

The PRF test is chosen to verify the slanted-edge MTF test partly because the test setup requires little adjustment (see Figure 1) between conducing the PRF test and the MTF test. This allows the operating conditions to be as similar as possible when comparing the results of the two tests. Additionally, the PRF test shares the advantage of the MTF in that the overall performance of the integrated optical system—detector and telescope system together—can be assessed in a single test in which the UUT operational parameters and simulated operational environment are taken into account. And just like the MTF test, the PRF data taken on the ground can be verified after launch. The PRF data can be measured after launch by allowing the telescope to point at a star, i.e., a point source[6].

In the PRF test, a point source is created by back-illuminating a pinhole with an integrating sphere. The point source is then translated into collimated space and is delivered to the UUT entrance pupil and ultimately to the UUT FPA. Change in focus position through focus produced by incrementing a focus stage, allowing data to be generated. Ensquared energy is used as the PRF figure of merit for the purposes of verifying the best focus position. The best focus position is identified as the focus position that results in the tightest PRF, which corresponds to the PRF with the highest ensquared energy. Note that though the MTF and PRF are intrinsically linked by way of Fourier transforms, the two methods—i.e., the MTF test and the PRF test—are used to arrive at their respective results separately and are treated and analyzed independently.

3. DATA ANALYSIS AND RESULTS

3.1 Test setup

The test setup for the slanted-edge MTF test and the PRF test are extremely similar. The MTF test was conducted first, then the PRF test was conducted immediately afterwards. Both tests are conducted at the same temperature for the purposes of focus position verification. Figure 1 shows the test setup; the only key difference between the setup of the two tests is that the MTF slanted-edge target is replaced with a 15 micron pinhole. Before and after taking data, the MTF target or pinhole location is aligned to be at the focal point of the collimator optics. The MTF target or the pinhole is back-illuminated with a uniform light source produced by an integrating sphere, the light source is collimated, and then a steering mirror folds the optical path in collimated space to be presented to the entrance pupil of the UUT and focused to the FPA. A focus stage is moved collinear to the optical axis of the test system with the MTF target or pinhole at infinite conjugate to produce an effective focus shift in image space through longitudinal magnification.
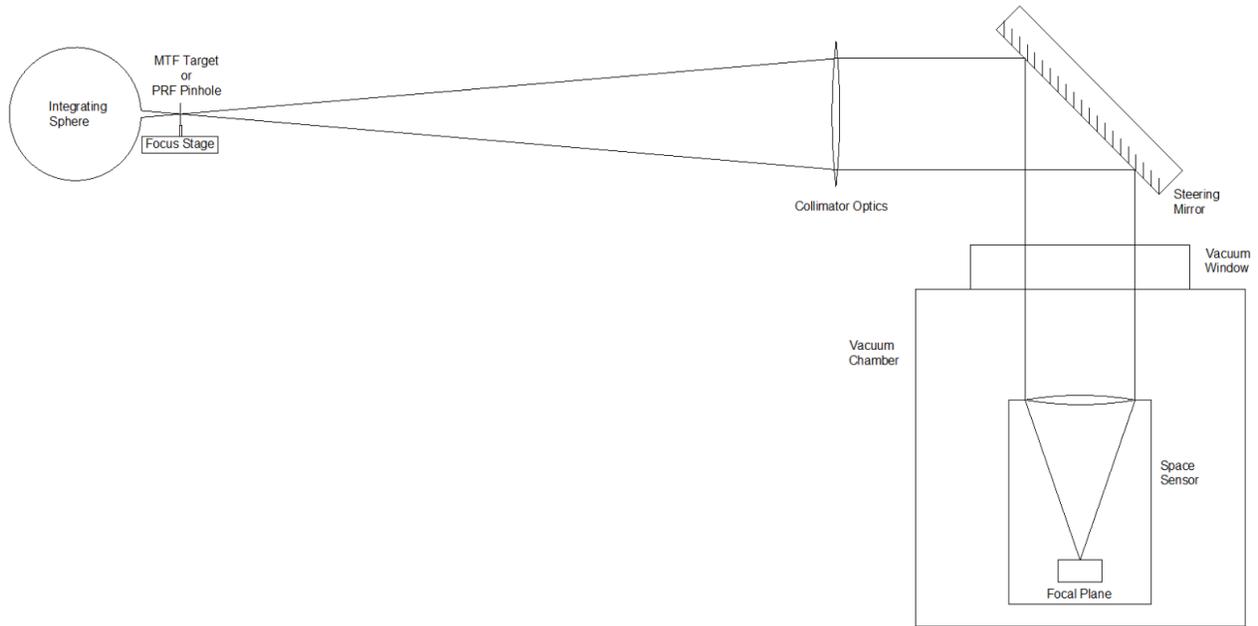
Figure 1. Slanted-edge MTF and PRF setup[1]

3.2 MTF Results

The aforementioned test setup is used to image orthogonal slanted edges of the MTF target on the focal plane. Images are taken through focus by adjusting the position of the collimator focus stage between images. These images are processed, and the modulation of the OTF is calculated and plotted in a three dimensional plot shown in Figure 2 versus spatial frequency and focus position. The best focus position is determined to be the focus position that provides the highest MTF at the chosen spatial frequencies.
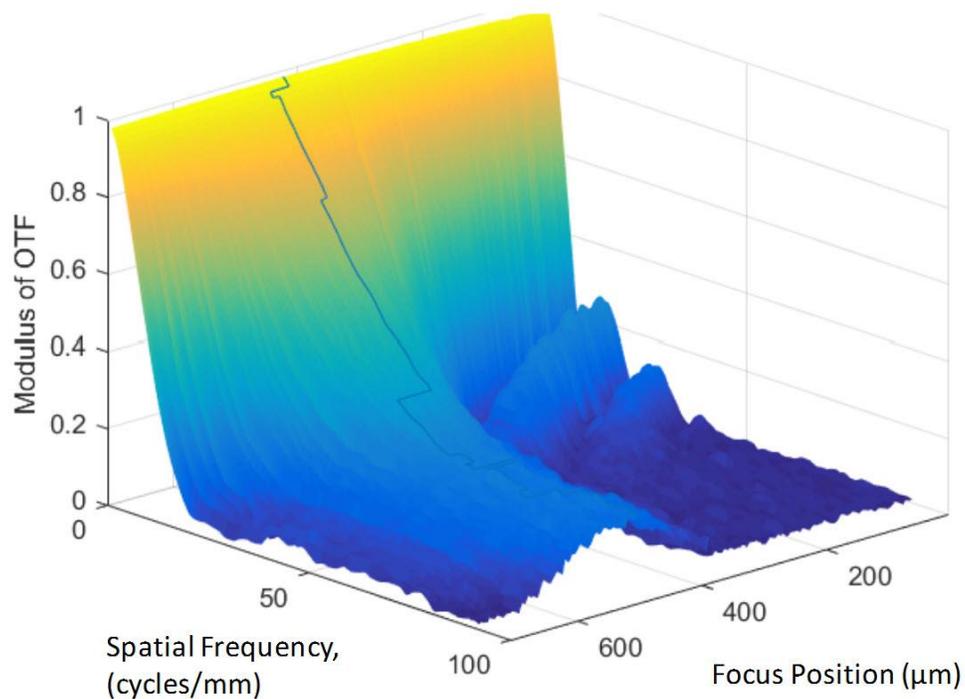

Figure 2. Example plot of measured MTF as a function of focus position and spatial frequency[1]

Analysis of vertical edges provides sagittal MTF results whereas analysis of horizontal edges provides tangential MTF results. Since the optical telescope assembly under test has substantial astigmatism, it is critical to consider both tangential and sagittal results for establishing OTA best focus. Further post-processing is completed to remove noise and decrease data uncertainty producing Figure 3 and Figure 4, the resultant plots of best focus position versus spatial frequency for tangential and sagittal best focus, respectively. Relative focus position is measured from the collimator focal point location translated to image space (where the FPA is located) with a longitudinal magnification factor. Best focus is calculated by taking the average of the tangential and sagittal best focus positions giving the medial best focus position. By taking the median of the data shown, the tangential and sagittal best focus positions were found to be -0.0903 mm and -0.7181 mm, respectively. The medial best focus position is then indirectly derived to be -0.4042 mm. This relative focus position, in more meaningful terms, corresponds to offsetting the UUT FPA by 0.4042 mm away from the primary mirror to arrive at the resulting best focus position.
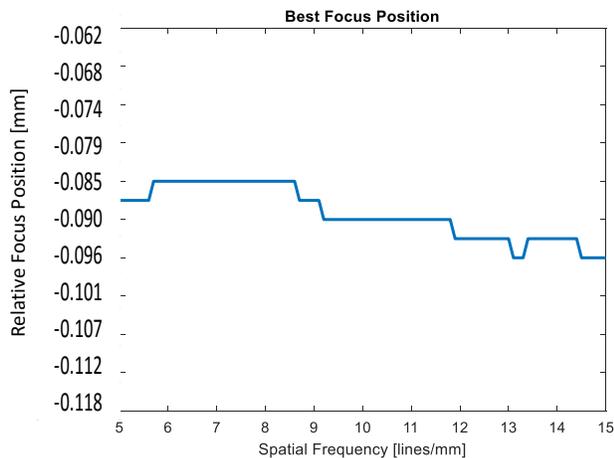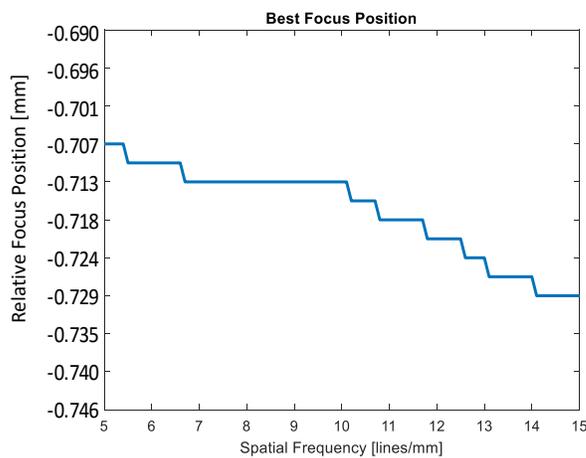

Figure 3. Tangential best focus

Figure 4. Sagittal best focus

Figure 4 shows that the best focus position is dependent on spatial frequency. Optical model simulation of a similar OTA predicts a dependency of best focus position on spatial frequency for optical systems dominated by aberration[1]. The form of the dependency is dependent on the aberration content where astigmatism shows a very distinct dependency of best focus with spatial frequency. We understand from the manufacturer that the astigmatism in this system is primarily caused by gravity sag and will not be present in its zero gravity space operational environment. For this reason, low spatial frequencies between 5 and 15 lines per mm are analyzed to minimize any best focus position bias error stemming from the non-zero relationship between best focus position and spatial frequency.

For space sensors operating in a zero gravity environment, it is recommended to include gravity-flip test results in the determination of best focus positions[1].

3.3 PRF results

Using the same test setup with the PRF test target in place of the MTF target, images of the PRF are taken through-focus by incrementing the focus stage position, producing an effective focus shift. The data is processed to reduce noise and identify regions of interest (ROI), then a plot of ensquared energy as a function of relative focus position is generated like that shown in Figure 5. Ensquared energy is calculated by dividing the response of a small square group of pixels (or alternatively, a single pixel) centered on the PSF by the summed response of a larger square area on the detector. The focus position that yields the tightest, i.e., highest, ensquared energy, is considered to be the best focus position. A quadratic curve fit is applied to a portion of the data to help negate random noise and determine the best focus position. Relative focus position is measured from the same position as that of the MTF data—the collimator focal point location mapped to image space. As shown in Figure 5, the best focus position is found to be -0.3499 mm using the ensquared energy PRF test method.
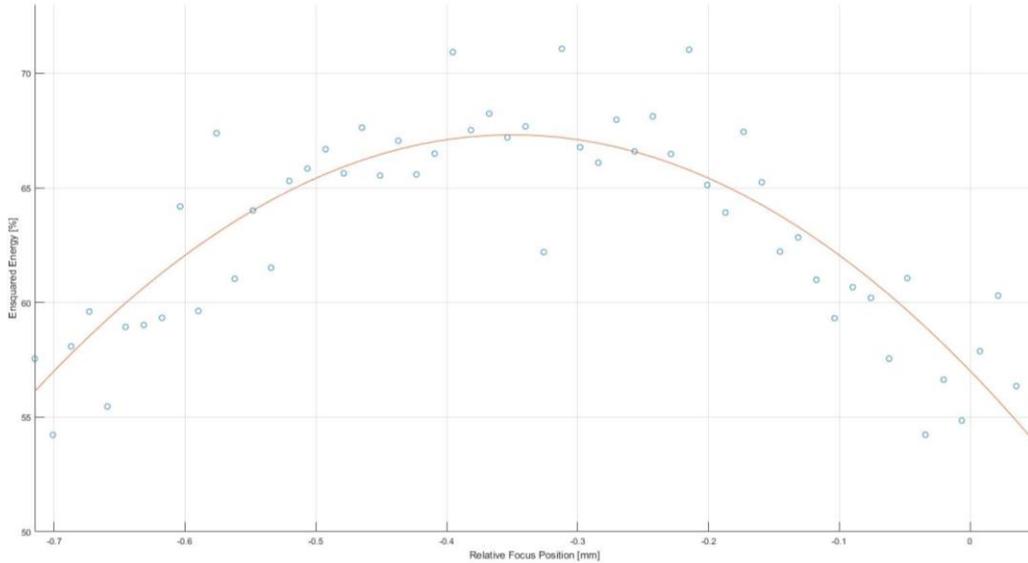
Figure 5. Ensquared energy plotted as a function of relative focus position, with a curve fit through a selection of the data

The noise in Figure 5 is largely tied to pixel sampling. The noise associated with pixel sampling is made worse, particularly near the peak, by a necessary interpolation in the pixel filter pattern of the non-monochrome FPA. Due to the limited timeframe of testing inside the vacuum chamber, multiple images of each scan position were not able to be taken for this data. This results in the disadvantage of not being able to average multiple frames to further decrease the noise tied to pixel sampling in post-processing the data. However, the majority of the data is relatively well-behaved. This is assisted by a summation of a larger box of pixels (as opposed to one pixel) in the ensquared energy calculation to improve SNR and decrease uncertainty. Additionally, sources of noise, such as air turbulence and vibration, are reduced by making use of an intensity-weighted centroid, but pixel sampling ultimately limits the fruits of this technique.

Example PRFs are shown in Figure 6 for three different focus positions. The astigmatism is clear upon noticing the elongation of the PRF in the defocused positions. The PRF in the center of the figure corresponds to a PRF that is close to the best focus position, while the other two PRFs are defocused in focus position. The sagittal PRF in Figure 6 corresponds to a focus position on the left-hand side of the relative best focus position (moving the FPA closer to the primary mirror compared to the best focus position), as plotted in Figure 5. Similarly, the tangential PRF in Figure 6 corresponds to a focus position to the right of the best focus (moving the FPA further from the primary mirror compared to the best focus position).
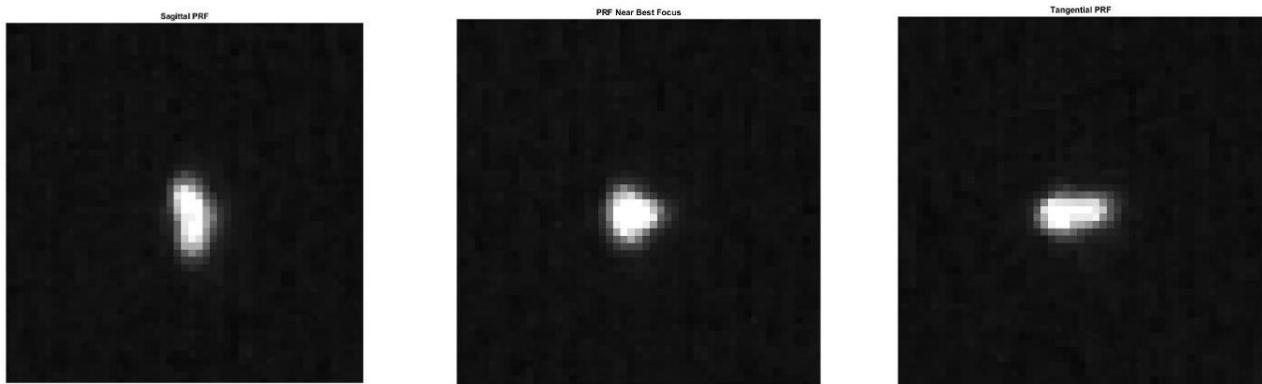

Figure 6. Three example test PRF functions for three different focus positions
Left: Sagittal elongation of PRF near relative focus position close to -0.7171 mm
Middle: PRF near resulting relative best focus position of -0.3499 mm
Right: Tangential elongation of PRF near relative focus position of -0.0903 mm

3.4 OTA focus tolerance budget

A focus tolerance budget has been created for setting the fixed focus on the OTA within 30 μm. The MTF and PRF focus test methods discussed in this paper are considered in establishing this budget.

Contributions to the focus uncertainty budget in the object space FPA best focus position are estimated for the test setup as shown in Table 1. Due to the strong similarity between the test setup of the MTF and PRF tests, the test setup uncerties shown in Table 1 represent both tests. The test setup uncertainty is dominated by the focus stage stability. Since the collimator has a shorter focal length than the tested optical telescope assembly, focus stage errors are magnified by approximately the system's longitudinal magnification at the OTA focal plane. Because the collimator is metered with stainless steel and aluminum, small laboratory temperature fluctuations result in significant focus errors. Collimator focus and target alignment are measured before and after data capture, tracking the stability errors, and reducing the OTA focus tolerance stemming from the test setup. When the tests are conducted in a simulated operational environment, temperature effects drive the vacuum window to contribute 5 microns of uncertainty in the focus tolerance budget.

Table 1. Focus tolerance budget

Category	Description	Bilateral Tol. +/- Microns
Test Setup	Collimator WFE	0.5
	Collimator focus	0.5
	Focus stage accuracy	3
	Focus stage stability	10
	Knife edge or pinhole alignment	0.5
	Vacuum window	5
Measurement	Data analysis repeatability	10
	Measurement resolution	3
Shim	Shim fabrication tolerance	12.5
Margin	Focus margin	10
	Worst Case	52
	RSS	23
	MRSS[7]	**30**

Additional focus uncertainty is seen in the measurements. Vibration, air turbulence, and detector sampling result in increased data analysis repeatability uncertainty for both focus test methods. For both the MTF and PRF data analysis, multiple data points are taken and fit to reduce the data analysis repeatability tolerance to approximately 10 μm. Measurement resolution is a function of the through-focus step size in data acquisition.

The shim fabrication for the FPA mechanical alignment is given a tolerance of +/-12.5 μm. This allocation includes center thickness and any wedge requirements for the shim. Lastly, 10 μm of focus margin is allocated to conservatively account for potential error in estimates in the measurement focus uncertainty budget.

Total focus tolerance for the MTF and PRF data is summed using a modified root sum of the squares (MRSS) to +/-30 μm. The modified RSS includes the number of independent error sources in the statistical summation[7].

A rigorous measurement uncertainty analysis has not been completed to date. Focus measurement test uncertainty budget estimates considered in generating Table 1 are based on loose calculations from the data that is currently available. Additional test data combined with statistical analysis is planned.

3.5 Comparison of results

The slanted-edge MTF test resulted in a relative focus position of -404.2 microns, and the PRF test resulted in a best focus position of -349.9 microns. The two different focus position results have been identified in Figure 7, and the approximate corresponding PRFs have been shown, for reference, in Figure 8. The left vertical line shows the best focus position found from the MTF test, and the right vertical line shows the best focus position found from the PRF test (the maximum of the curve fit). The left image in Figure 8 shows a PRF near the MTF focus position result, and the right image shows that of the PRF focus position result. It is important to keep in mind that the PRF images in Figure 8 do not accurately show what the PRF will look like when the OTA is in a zero-G environment; this is discussed in more detail below in what we expect,

should multiple gravity orientations be tested. The PRFs shown in Figure 8 pertain to what would be seen for a terrestrial optical system, for which a single gravity orientation acts on the optics.
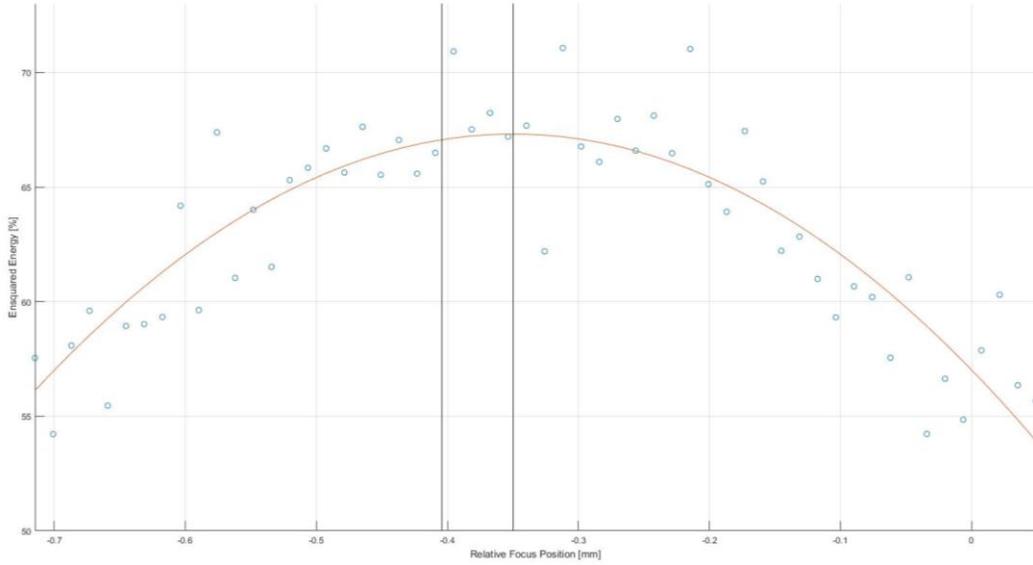

Figure 7. Ensquared energy plotted as a function of relative focus position, with a curve fit through part of the data and best focus positions from both methods identified for a single gravity orientation
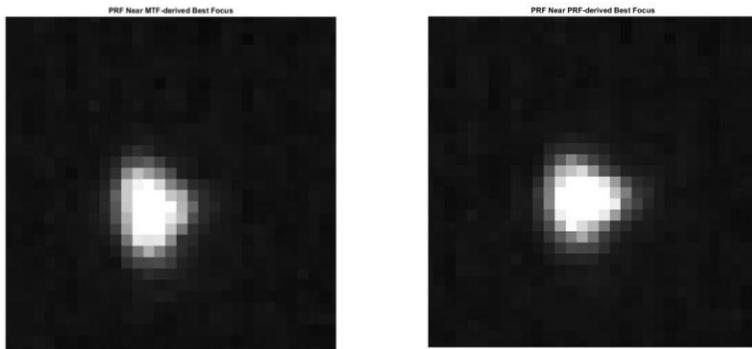

Figure 8.
Left: PRF near the MTF-derived best focus result in a single gravity orientation
Right: PRF near the PRF-derived best focus result in a single gravity orientation

It is strongly suspected that the discrepancies between the MTF and PRF focus position results are caused largely by the differences in how the methods find the medial best focus of the astigmatism-dominated OTA. It is important to note that the MTF test finds the sagittal best focus position and the tangential best focus position independently. These focus positions are then averaged to find the medial best focus. On the other hand, the PRF test directly measures the medial best focus by using an ensquared energy calculation.

This suspected source of the discrepancies is supported by identification that the PRF best focus is biased closer to the tangential MTF best focus position. The tangential MTF performance at the tangential best focus is greater than the sagittal MTF performance at sagittal best focus, which contributes to this offset. The slanted-edge MTF test, as described herein, does not account for the magnitude of the aberration in the sagittal or the tangential best focus position. Considering the magnitude of the aberration may affect the results of the MTF test. The offset direction between the MTF and PRF results is as expected, as can be recognized when referencing Figure 7. Additionally, the spatial frequency may play a role in the discrepancy for the sagittal and tangential best focus positions are dependent on spatial frequency.

The OTA under test is dominated by astigmatism induced by gravity sag. Upon deployment in its zero-gravity space environment, the sag is relieved and approximately 90% of the astigmatism aberration is removed. MTF testing of a

separate UUT has been completed with two gravity vector orientations to find the approximate zero-gravity best focus position[1].This test and modeling effort determined that the best focus performance is approximately symmetric about the zero-gravity best focus position such that an average of the two gravity orientations results in the best focus position. We anticipate that this will also be true for the PRF testing approach. However, at this time, PRF testing in multiple gravity vector orientations has not been completed. Specifically, we expect an approximately equivalent but opposite offset of the PRF result from the MTF best focus result in the 180-degree gravity orientation as compared to the 0-degree orientation. This expectation is supported with the observation that the difference in the magnitude of the aberration content (corresponding to a larger peak MTF) of the tangential and sagittal best focus positions biases the PRF spot behavior, and therefore influences best focus position found from the PRF test. The tangential best focus position consistently has a greater peak MTF for this OTA, and upon flipping the gravity orientation, the tangential best focus position is found to swap sides with the sagittal best focus position[1]. Therefore, it is expected that the location of the tightest PRF, for two antiparallel gravity orientations, is offset in opposite directions, depending on the gravity orientation. On the other hand, the MTF test is not affected by the magnitude of the aberration; the MTF test finds the best focus position by first finding the tangential and sagittal best focus positions then averaging those results. With this in mind, it can be hypothesized that the MTF test is less gravity influenced than the PRF test. An average of the results of two PRF tests in two opposing gravity orientations would result in a near equivalent best focus answer compared to the average of the results of two MTF tests in two opposing gravity orientations. We recommend completing this testing in order to validate this theory.

4. CONCLUSIONS

A slanted-edge MTF test has been successfully developed for measuring the best focus position of an optical telescope assembly. Testing has been completed to establish best focus of an optical telescope assembly. PRF testing has subsequently been completed in an effort to verify best focus position testing. The initial results show a 54 μm discrepancy between the two methods. This discrepancy is larger than predicted uncertainties for the two methods. The 54 μm difference is believed to be due to each test's different approach to finding the best medial focus of an astigmatism-dominated OTA. The MTF test finds the best focus position by way of identifying the sagittal best focus and the tangential best focus and averaging results, while the PRF test finds the best focus directly by way of ensquared energy. The combination of these tests allows us to identify unique, tailored characterization testing approaches for this UUT. Further testing of both the PRF and MTF in two antiparallel gravity orientations (under the same operating conditions and environment) is the first and most important step towards better matching best medial focus position results.

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