2.4 Optics Quality

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1. Introduction

The MagAO-X instrument's performance depends on the quality of the contrast produced at the coronagraphic focal plane. The major contributor to the contrast result is the surface quality of the reflective optical elements. This document describes how we measured the optics quality and simulated their performance in MagAO-X. The quality is studied using a power spectral density (PSD) analysis in Section 2. The PSD characteristics are compared to the specifications chosen from the Preliminary Design Review (PDR). The dark hole (DH) contrast performance is calculated using a Fresnel propagation analysis in Section 3.

2. Optical Quality Characterization: Measuring PSDs

This section will describe the process for measuring the optics and calculating the quality through a PSD. We measured the flat mirror optical surfaces using a Zygo Verifire Fizeau interferometer in the Extreme Wavefront Control Laboratory. The flat mirrors surfaces had piston, tip, and tilt removed using Zygo's proprietary software. The off-axis parabola (OAP) mirror surface maps were provided to us directly from the vendor (Nu-Tek). Fig. 1 features a sample flat mirror optical surface map. Fig 2 features optical surface maps for all the OAP mirrors.

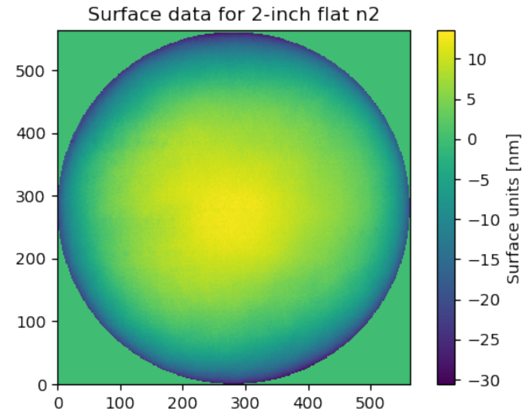

Fig. 1.—: Sample laboratory measured optical surface used in MagAO-X, 2-inch flat mirror featured. Surface units in nanometers at 100% clear aperture.

To analyze the optical surface quality, a PSD calculation was performed with each mirror. An

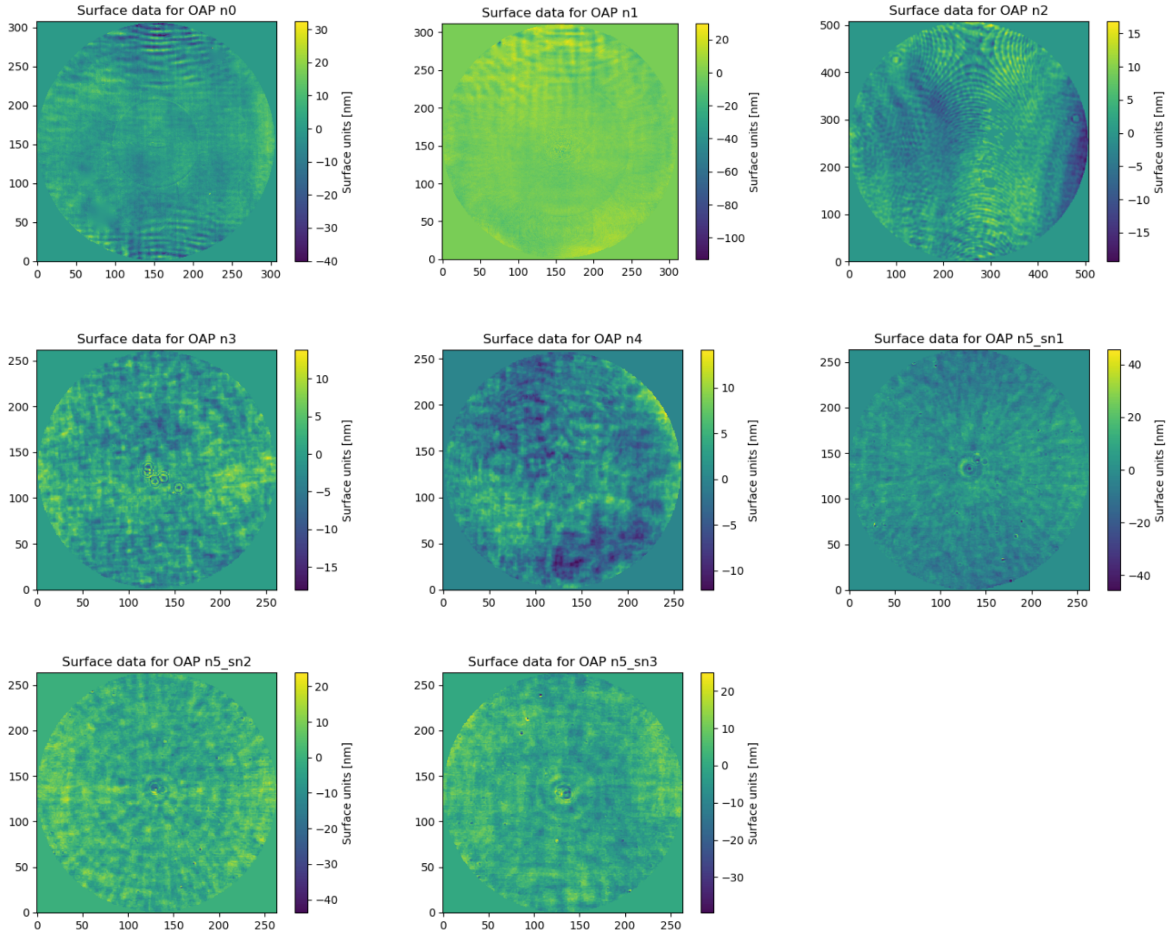

Fig. 2.—: Sample laboratory measured optical surfaces used in MagAO-X, featuring all 2-inch OAP mirrors. Surface units in nanometers at 100% clear aperture.

explanation for the PSD process can be found in the PDR. The PSDs are computed with the measured optical surface data at a particular clear aperture (CA) region. A 2D Hanning window is applied to prevent high frequency leaking. An average PSD was calculated for each set. Each measured PSD was variance normalized, averaged at each sampled spatial frequency, and scaled by the average variance of the surfaces. The bandwidth limits, unless stated otherwise, are generally tested with 1/CA diameter for the lower boundary and the Nyquist limit for the upper boundary.

Fig. 3 and 4 feature the PSD generated and modeled for the 2-inch flat mirrors (set of 8 total) at 20% CA (10.16 mm) and the OAP mirrors at 80% CA (40.64 mm) respectively. The black line in each plot is the average PSD profile for all the measured optics in the group. The average surface RMS values for the flat mirrors at 20% CA is 0.529 nm and the OAP mirrors at 80% CA is 4.159, which are both $< \lambda/100$ quality. While there is power featured in the lower spatial frequencies, the PDR specifications

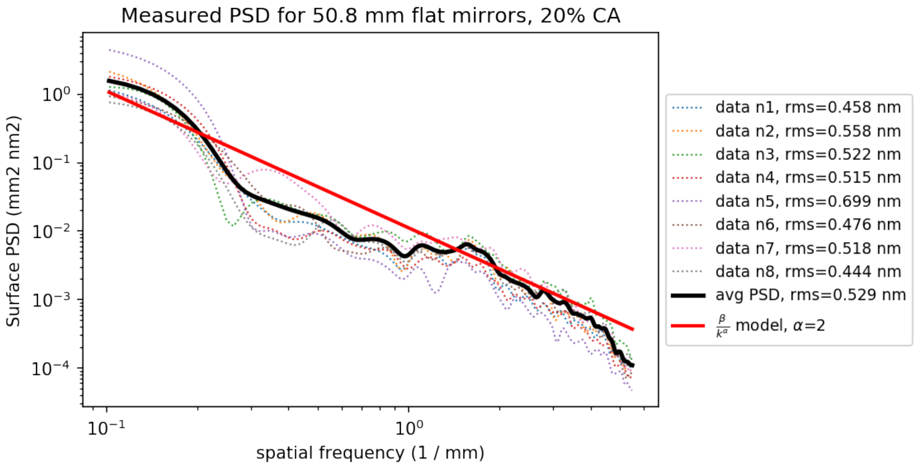

Fig. 3.—: PSD calculation and model for 2-inch flat mirrors

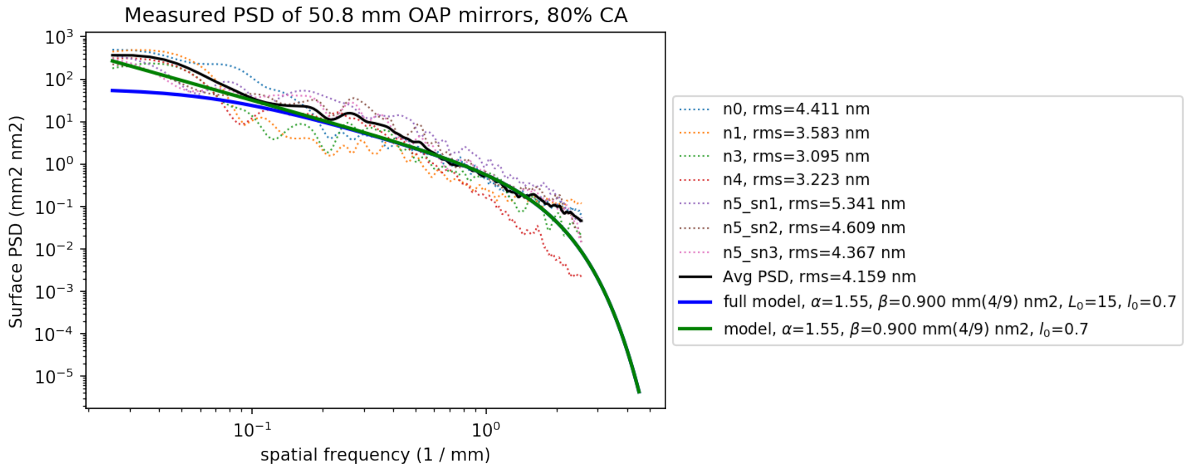

Fig. 4.—: PSD calculation and model for 2-inch OAP mirrors at 80% CA

focused primarily on having low power in the higher spatial frequency modes.

The PSDs here are compared against the model forms with the parameters of α, β, L_0, and l_0 implemented based on assumptions made in the PDR. The β value is dependent on the spatial frequency bandwidth upper and lower limits, the CA diameter, variance, and a value for α. We assume α=1.55 for OAPs and α=2 for flat mirrors from the PDR. The outer scaling (L_0) and inner scaling (l_0) are not assumed for flat mirrors, but we set them to L_0=15 and l_0=0.3 for OAPs. The red line in Fig 3 is the basic PSD model assuming only the PDR values of α and β. The pattern for this is following the trend, so the as-purchased optical flats are within parameters of assumed in the PDR. The basic PSD models for the OAP are featured in the green and blue lines in Fig 4. The blue line is the full PSD model assuming all the α, β, L_0, and l_0 parameters listed in the PDR. The green line is the same PSD model except only α, β, and l_0 are considered. The elimination of the L_0 parameter was included since it was not obvious from the optical surface maps provided by the vendor whether they were tested enough to see the low order spatial frequency flattening. However, the green and blue lines merge at some point in the mid-spatial frequency regime and follow through to the high order spatial frequencies. While the data's upper spatial frequency range is cut off by the Nqyuist limit, the green and blue lines both show where the higher order spatial frequencies would lead with the data. Comparing these basic models with the average measured OAP PSD plots show that the as-purchased OAP mirrors are within the parameters assumed in the PDR.

3. Optical Quality Performance: Fresnel Analysis

Ultimately, the optics quality performance is based on the DH contrast created at the MagAO-X coronagraphic focal plane science camera. This is explored through an E2E Fresnel propagation test of the system. This section will cover 3 different tests to evaluate the optical surfaces performance:

1. Section 3.2 covers an E2E simulation with no optical surface aberrations induced (except the vAPP coronagraph). This functions as MagAO-X's diffraction limited optimal performance.
2. Section 3.3 examines an open-loop E2E simulation including all optical surface aberrations. This functions as the lower limit contrast if no corrections was implemented.
3. Section 3.4 analyzes a closed-loop E2E simulation with all optical surface aberrations induced and a simulated correction placed onto the tweeter DM. This will produce an expected surface aberration correction contrast and verify that the optical elements procured will not hinder MagAO-X's performance.

3.1. Building MagAO-X in POPPY

POPPY (Physical Optics Propagation in PYthon)(1) is the primary software used for MagAO-X's Fresnel diffraction analysis. The field propagation is calculated using Fresnel approximation and angular spectrums(2). The source code is free to download[1]. A complete description of POPPY and its procedural process for MagAO-X can be found in the PDR document. The POPPY program parameters used in this document can be found in Appendix A.

Each Fresnel propagation test performed in Sections 3.2, 3.3, and 3.4 all assume the same sampling parameters (see Appendix A). Since POPPY assumes paraxial approximations, applying a common

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[1] https://github.com/spacetelescope/poppy

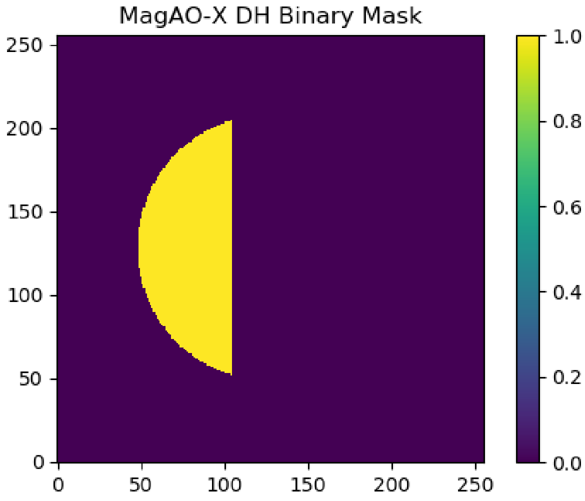


Fig. 5.—: Binary DH mask used for POPPY simulations of MagAO-X

binary mask will measure each test correctly since each of the science focal planes will be at the same scale. Fig 5 shows the binary mask used for selecting DH active pixels to calculate the average contrast. All contrast calculations are scaled according to the brightest pixel in its own test, not scaled according to another test's ranges. Note that the PSF focal plane detector presented here is ideal and noiseless.

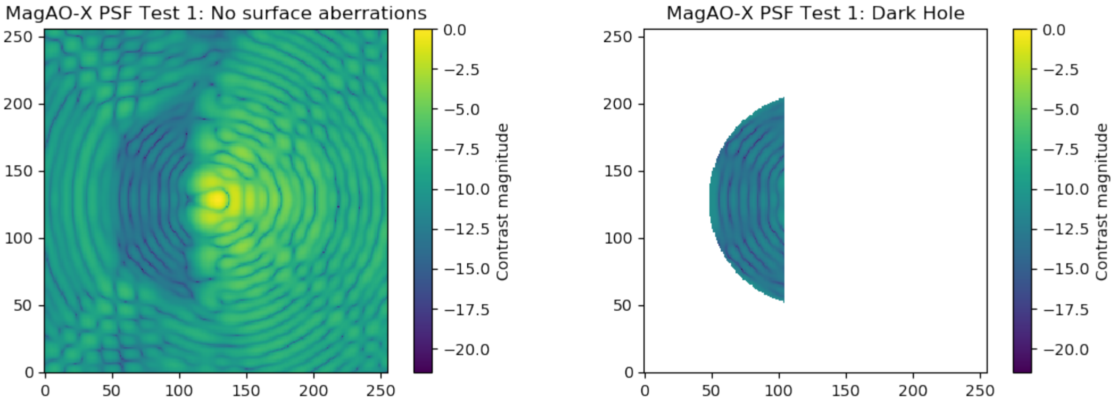
3.2. Performance test 1: E2E open-loop without optical surfaces

This test is the diffraction limited performance for the MagAO-X optical system. This was done by assuming every optical surface was perfectly flat with no aberrations.

Fig. 6 features the PSF results for this test and masking out the DH region itself. The average contrast value inside the DH mask contrast calculated at this state is 4.190E-6 and serves as the optimal DH contrast for MagAO-X.

3.3. Performance test 2: E2E open-loop with optical surfaces

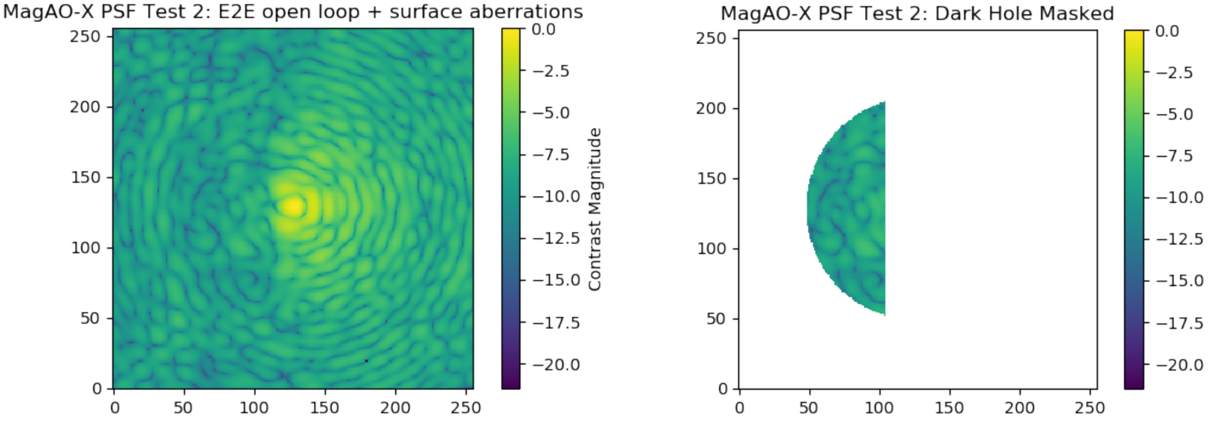
Applying optical surface aberrations will attenuate the MagAO-X contrast performance. It is unavoidable, as optical surface precision directly influences cost. This test is similar to that in Section 3.2 except inserts random surface maps on every reflective optic. We perform this test to examine the extent of performance alteration based on the procured optics for MagAO-X. These random surface maps were generated using the PSD parameters set in the PDR, which were confirmed in in Section 2. So, the DH contrast performance here would be within expectation of the E2E open loop performance for MagAO-X,



(a) PSF at Science Focal Plane (b) Masked DH Region

Fig. 6.—: Fresnel propagation results at science focal plane for E2E open loop with no surface aberrations present

assuming no corrections are set in place.



(a) PSF at Science Focal Plane (b) Masked DH Region

Fig. 7.—: Fresnel propagation results at science focal plane for E2E open loop test with surface aberrations present

Fig 7 features the PSF results and DH region for the E2E open-loop with optical surfaces test. Note that the DH in Fig 7b is looking drastically different from the optimal DH in Fig 6b. The average contrast in this test is 1.773E-4, which is already a 2 magnitude increase from the DH contrast for the perfect surfaces test. This contrast level is the lowest contrast limit that MagAO-X would produce if no correction is made for the optical surfaces.

3.4. Performance test 3: Closed-loop optimal DM flat correction

Since there was a 2 magnitude DH contrast attenuation created by the optical surfaces alone, it is critical that a closed-loop correction cycle is incorporated. We implement here a simple pupil plane correction loop to verify that the tweeter DM may correct higher spatial frequency content surface imperfections without consuming all the available stroke range. This test is an additional test since the PDR to ensure that the performance of the optics will not limit MagAO-X's science capability.

A few things to note about this simulation is that the DM surface correction generated is not matched to the physical tweeter DM's actuator mapping. Additionally, the corrections are made without the vAPP coronagraph present to separate its influence on optical surface aberrations. Lastly, the correction gains are set to 1 since this is a static system analysis.

The DM correction loop begins the Fresnel propagation from the telescope entrance pupil to the Lyot stop pupil plane (shortened to Lyot plane), where the wavefront sensing begins. The significance of the Lyot plane location is that it is the final pupil plane location prior to the science focal plane PSF. Of the 23 total optical surfaces in MagAO-X, 20 of them will have been detected at the Lyot plane and be available for correction. The Fresnel analysis allows exact knowledge of the complex wavefront at the Lyot plane. The bottom left element in Fig 8 is the Lyot plane phase for the E2E open loop configuration with the same set of simulated optical surfaces used in Section 3.3 and assumes the tweeter DM has a perfectly flat surface. The Lyot plane phase undergoes a spatial frequency low pass filter based on the tweeter DM bandwidth capability. The filtered phase is inverted into negative OPD values, which creates the tweeter DM mapping correction. A first OPD correction is shown in the top row second column of Fig 8.

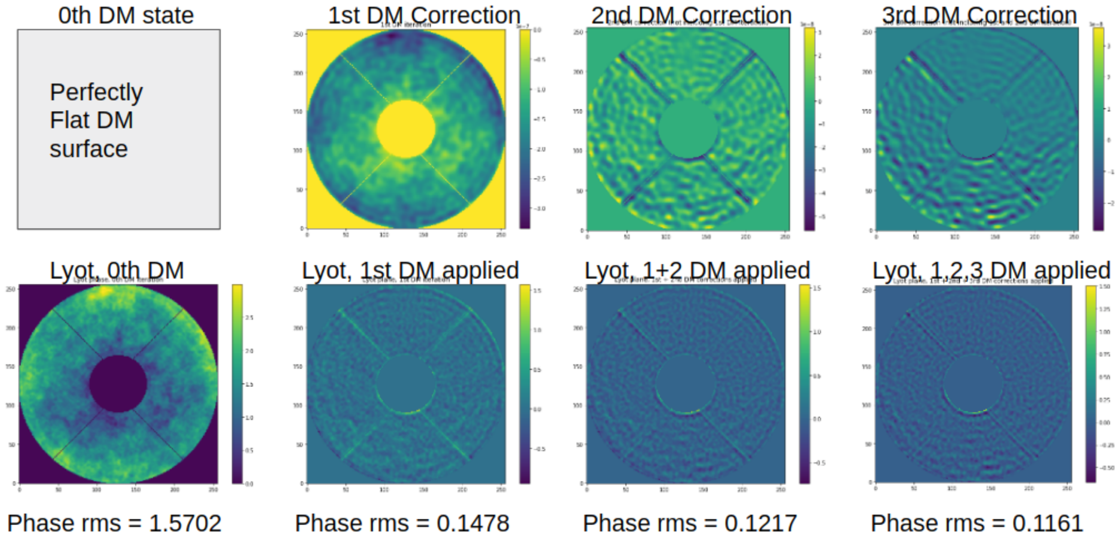
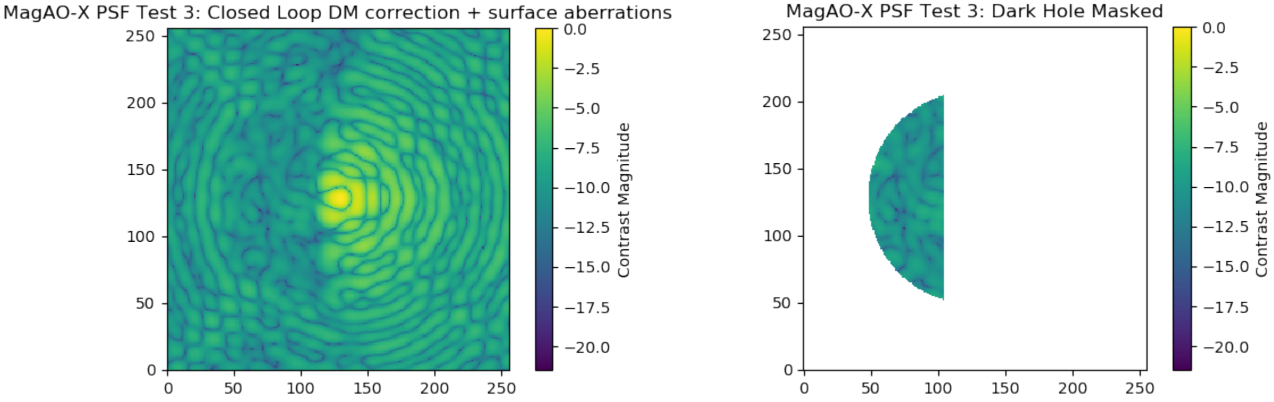


Fig. 8.—: First 4 Lyot phase states based on 3 DM correction cycles

The whole Fresnel analysis is run again but with the OPD correction surface inserted as the surface map for the tweeter DM. This process is repeated several times until the Lyot plane phase RMS approaches a steady state. Fig 8 shows a 3 sequence loop correction for the DM. The goal of the correction loop is to push the Lyot plane phase as close to 0 radians, which implies a wavefront with low aberration present. After 7 iterations of the loop, the Lyot phase RMS hits steady state around 0.101 rad, which is an improvement of 94%. The final DM correction OPD surface is then used as the tweeter DM surface map to calculate MagAO-X coronagraphic DH contrast.



(a) PSF at Science Focal Plane

(b) Masked DH Region

Fig. 9.—: Fresnel propagation results at science focal plane for closed loop DM correction with surface aberrations present

Fig 9 features the PSF results and DH region for the closed-loop optical surface correction. The average contrast in the DH region of Fig 9b is 5.559E-5, which is a 1 magnitude improvement from the E2E open loop non-correction test in Section 3.3. This final DH contrast is a low-level expected contrast performance for MagAO-X on a static level.

There are several potential causes to why the DM corrected contrast is still 1 magnitude lower than the optimal contrast calculated from Section 3.2. One reason is that the collection of spatial frequency content beyond the low pass filter is not getting incorporated in the DM correction and is enough to impact the contrast by 1 magnitude. This is an issue placed by the physical limits of the tweeter DM. Another potential cause is that the 3 optical surfaces present between the Lyot plane and the science detector are contributing to the contrast change. These optics are not seen by the Lyot plane pick-off point and the correction loop is blind to their impact. A solution to this is to place the best quality optical surfaces at these locations to minimize dark hole contrast degradation. Additionally, these surfaces may be corrected using focal plane wavefront sensing in the control loop, as the science focal plane will see the impact across all the optical surfaces. This will require additional analysis for future work.

4. Summary

The Fresnel analysis has shown the MagAO-X optical performance through the dark hole contrast. We measured the as-purchased optical elements and calculated the quality using a PSD. We compared their measured performance with a PSD model based on the PDR and show that we are within the specifications. We show how a simple correction loop implemented on the tweeter DM can alleviate 1 magnitude of contrast in the dark hole with realistic optical surfaces in place. We compare the results in three different configuration and show that the expected output for the MagAO-X optical system will produce 5.559E-5 contrast, which is within expectations.

A. POPPY program parameters

The POPPY project is a work in progress, therefore different versions may affect the results rendered in the MagAO-X Fresnel propagation analysis. We list here the various details and assumptions made in the analysis presented in this document.

The following optical element assumptions were implemented through POPPY:

- Optimized DM surface maps (does not take into account physical DM mapping)
- Perfect wavefront sensors at each detector field (Lyot pupil plane, science focal planes)
- No amplitude alteration from optical surface PSD implemented
- No broadband analysis (monochromatic at H-alpha wavelength, 656nm)
- All optical surfaces sampled at 256x256 pixels but calculated with 8x oversample for the Fourier Transform algorithms (total 2048x2048 px).

The following is a list of version control details regarding the MagAO-X POPPY Fresnel analysis used here:

- POPPY version: 0.8.1dev1324.dev1348

REFERENCES

M. Perrin, J. Long, E. Douglas, N. Zimmerman, A. Sivaramakrishnan, K. Douglass, and M. Grochowicz, "Physical optics propagation in python," 2017.

G. Lawrence, "Optical modeling," Applied Optics and Optical Engineering **XI**, p. 125, 1992.

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