

# Modeling coronagraphic extreme wavefront control systems for high contrast imaging in ground and space telescope missions

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## ABSTRACT

The challenges of high contrast imaging (HCI) for detecting exoplanets for both ground and space applications can be met with extreme adaptive optics (ExAO), a high-order adaptive optics system that performs wavefront sensing (WFS) and correction at high speed. We describe 2 ExAO optical system designs, one in each regime, and examine them using the angular spectrum Fresnel propagation module within the Physical Optics Propagation in Python package. We present an end-to-end (E2E) simulation of the MagAO-X instrument, an ExAO system capable of delivering 6e-5 visible-light HCI for static, noncommon path aberrations. We present an E2E simulation of a laser guidestar (LGS) companion spacecraft testbed demonstration, which uses a remote beacon to increase the signal available for WFS and control of the primary aperture segments, providing <10 factor improvement for relaxing observatory stability requirements.

**Keywords:** adaptive optics, wavefront control, Fresnel propagation, testbed modeling

## 1. INTRODUCTION

Large segmented aperture ground and space based telescopes are undergoing development to enable direct imaging for extrasolar planets. For ground-based systems, Giant Magellan Telescope is planned for first light in the mid-2020's. Future space-based segmented aperture telescope missions, such as LUVOIR (Large UV Optical Infrared Surveyor), will have picometer-level observatory stability requirements for detecting Earth-like planets within the habitable zone. The challenges of high contrast imaging for both ground and space applications can be met with extreme adaptive optics (ExAO), a high-order ( $\geq 1000$  degrees of freedom) adaptive optics (AO) system which performs wavefront sensing and correction at high speed ( $\geq 1\text{KHz}$ ).

We describe two extreme wavefront control systems, one for ground and another for space currently in development. These optical system designs are examined using the angular spectrum Fresnel propagation module within the Physical Optics Propagation in Python package. We present an E2E simulation of the MagAO-X instrument,<sup>?</sup> an NSF-funded ExAO upgrade for the Magellan Clay 6.5-meter telescope at Las Campanas

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Observatory in Chile. The MagAO-X simulation implements simulated optical surfaces generated from power spectral densities on each optical element and a vector Apodizing Phase Plate (vAPP) coronagraph. MagAO-X’s contrast is measured in the vAPP dark hole region after using a deformable mirror (DM) correction. For large aperture segmented space telescopes, we analyze a laser guidestar<sup>1</sup> (LGS) companion spacecraft which uses a remote beacon to increase the signal available for wavefront sensing and control of the primary aperture segments. The LGS (potentially as small as a 6U or 27U cubesat) will fly in formation at a distance from the telescope (such as 10,000 km to 80,000 km), with the goal of increasing the speed and performance of the wavefront control system and relaxing the stringent stability requirements on observatory stability. We present the E2E simulations preliminary results of the LGS demonstration testbed, which is currently being built at the University of Arizona’s Wavefront Control Laboratory. With MagAO-X and LGS, we show how extreme wavefront control efforts on both ground and space systems will enable high-contrast exoplanet direct imaging.

## 2. SOFTWARE: PHYSICAL OPTICS PROPAGATION IN PYTHON (POPPY)

We present the E2E simulations preliminary results of segmented aperture space telescope wavefront sensing capability given a LGS. The software used for Fresnel analysis is Physical Optics Propagation in PYthon (POPPY)<sup>2,3</sup>. The POPPY source code is available online for free.<sup>?</sup> The POPPY framework allows users to build an optical system composed of multiple planes (pupils, images) from a flexible library of optical element classes. POPPY can model both Fraunhofer and Fresnel diffraction for wavefront propagation through an optical system, and has PSF formation capabilities. Unlike raytrace software, POPPY uses the paraxial approximation and assumes perfectly focusing optics.

### 2.1 Building systems with POPPY

In POPPY, the optical system is built by inserting an optical element and propagating the field generated from the optical element to a certain distance until the next optical element. The field propagation is calculated using Fresnel approximation and angular spectrums.<sup>?</sup> This process is repeated throughout the entire system, until the science detection plane.

### 2.2 Optical Elements

Since POPPY assumes that all optics inserted in the system will focus perfectly, many otherwise complex optical elements are represented in simple form. Parabolic mirrors are treated as quadratic lenses with a focal length parameter. Detection planes (focal planes, cameras), flat mirrors, and deformable mirrors are represented as scalar transmission locations.

POPPY has built-in functions that can build custom optical elements as transmissive or OPD phase surfaces. It can also induce an aberration at certain locations as a Zernike wavefront error (ZWFE). Fig. 1 features a segmented mirror generated with astigmatism induced on the surface. More details on this are featured in the LGS simulation (Sec. 4).

POPPY also allows the user to insert custom amplitude transmissive or OPD (converted from phase) optical elements into the system, thereby letting the user induce aberration at their discretion. The surfaces are applied when the optical element is declared in POPPY. This custom optical element feature has been used throughout the MagAO-X design analysis for custom pupils, optical surface quality, and the vAPP<sup>4</sup> coronagraph mask (see Fig. 2). See Sec. 3.1 for more details on the surfaces used in MagAO-X.

## 3. GROUND: MAGELLAN EXTREME ADAPTIVE OPTICS (MAGAO-X)

The goal of the MagAO-X Fresnel propagation simulation is to characterize the testbed layout’s influence on the DH contrast levels produced by the vAPP coronagraph. One major contributor to the contrast level is the optical surface imperfections of each optic. There are 23 optical element surfaces evaluated in the coronagraphic E2E path, excluding the woofer-tweeter DMs and vAPP coronagraph. From here, we broke the analysis into 2 major parts: determining the lowest possible contrast level for an E2E simulation (see section 3.2) and verifying the optical specification requirements set (see section 3.3).

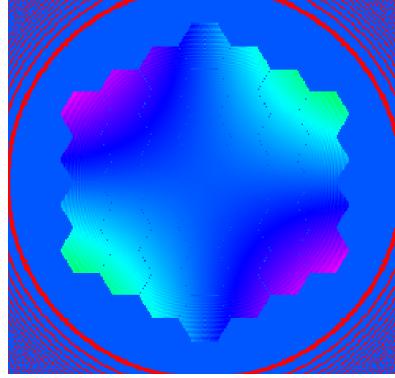


Figure 1. Sample custom optical element built using POPPY built-in modules. This is a segmented mirror with astigmatism induced, which is used for LGS in Sec. 4.

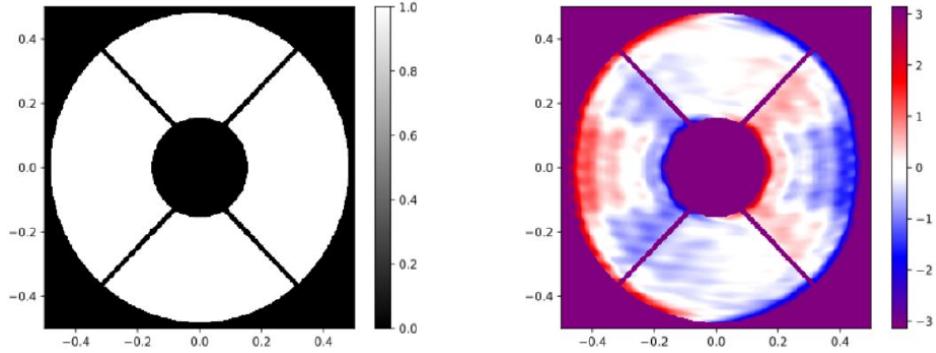


Figure 2. The vAPP coronagraph mask to be used in MagAO-X. The left image is the amplitude component, which is passed in POPPY as a transmission mask. The right image is the phase map, which is converted to OPD and passed into POPPY as an OPD surface map. The transmission and OPD surface maps are superposed together in POPPY to form a complex phase mask.

### 3.1 MagAO-X Testbed Model Description

In MagAO-X, the Fresnel propagation model uses the ZEMAX optical raytrace prescriptions set as the propagation distances between optics.<sup>5</sup> The E2E propagation path used is through the coronagraph science path, so the pyramid WFS is not included in the Fresnel analysis. See Fig. 3 for the MagAO-X testbed rendering.

Surface maps are generated using the MagAO-X optics specifications. The actual surface map of the Magellan Clay telescope primary mirror (M1) was used (see Fig. 4). For the other optics, PSDs were generated with the appropriate parameters and normalization. See Fig. 5 for sample PSDs generated. M2 and M3 are based on the known as-built surface specifications. For the new optics we used Vendor 1 High Precision for the OAPs, and assumed  $\lambda/100$  (PV) flats. The PSDs were used to generate surface maps by using standard Fourier convolution with Gaussian white noise.

The vAPP coronagraph used for high contrast characterization is for single DH generation. The initial DM surfaces were simulated as perfect surfaces, as the powered flat surface maps were not available at the time. All of these tests are performed assuming a bright source with no aberration. The wavelength used for the MagAO-X Fresnel analysis is H $\alpha$ .

### 3.2 Dark Hole Contrast Characterization

There are 3 different DH contrast characterizations calculated: the optimal DH contrast, the initial DH contrast for an open loop E2E setup with optical surfaces, and the DH contrast for a single-iteration closed loop E2E

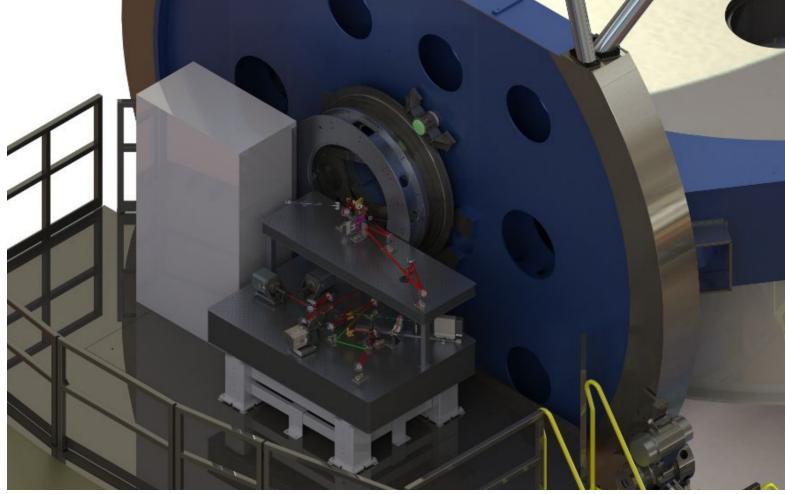


Figure 3. A rendering of the MagAO-X instrument on the Magellan Clay telescope platform.

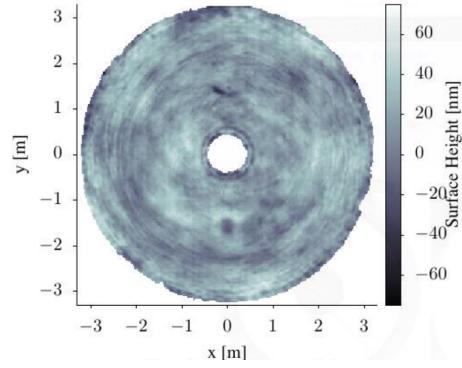


Figure 4. Measured surface map of Magellan Clay primary mirror

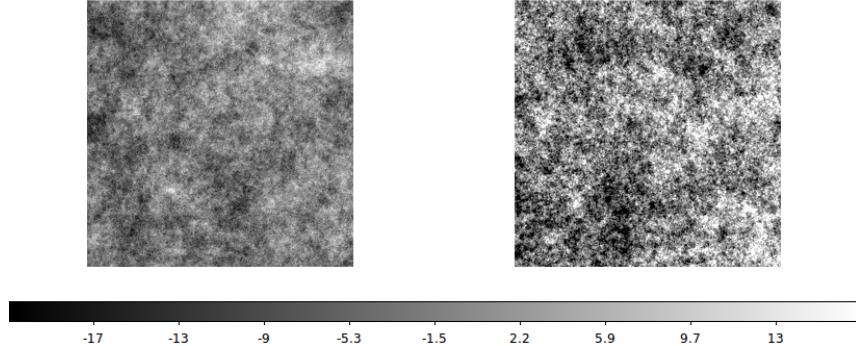


Figure 5. Sample PSD surface maps generated for MagAO-X in OPD units (nm).

setup with optical surfaces applied. The region of interest (ROI) used for calculating DH contrast in each test is a 54x54 pixel box inscribed within the DH region. The DH contrast is calculated by summing and averaging the individual pixels inside the ROI box of the fully-normalized image. The boxed ROI design choice was selected for quick comparison analysis. Future analysis will cover the entire dark hole. Each of the procedures are described and the contrasts values compared.

### 3.2.1 Optimal Dark Hole Contrast

The optimal DH contrast is calculated by running an open loop E2E simulation of the testbed but with perfect (unaberrated) surfaces set on each optical element. An unaberrated surface is set in POPPY by not applying a surface map at each optic, which is labelled in this paper as the "no surfaces" DH contrast. This contrast level sets the MagAO-X contrast limit and serves as a reference for the other tests. Fig. 6a features the coronagraphic PSF for the "without surfaces" test, which was found to be  $6.16e^{-6}$  and the best MagAO-X is capable of producing.

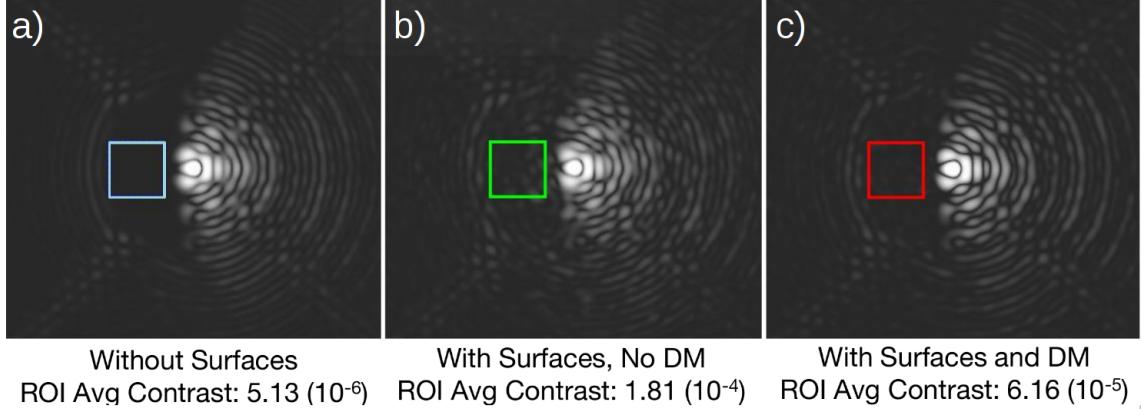


Figure 6. 9 MagAO-X coronagraphic PSFs generated through Fresnel propagation. The colored box represents the region of interest used in calculating the DH contrast for each particular test.

### 3.2.2 Open Loop E2E With Surfaces Applied

The second test is the initial DH contrast calculated for an open loop E2E simulation with all available optical surfaces inserted. Since it is open loop, the DMs remain as perfect surfaces and do not apply a correction. Its label is "with surfaces, no DM". This was done to observe how the planned optical surfaces affect the DH contrast and whether their specifications are sufficient enough to form a high contrast DH. Fig. 6b features the "with surfaces, no DM correction" coronagraphic PSF, which was found to be  $1.81e^{-4}$  contrast, which is 2 magnitudes below the optimal DH contrast.

### 3.2.3 Single Iteration Closed Loop Correction E2E With Surfaces Applied

The third test is another E2E simulation with optical surfaces implemented, but includes a single iteration closed-loop correction at the Tweeter DM surface. Its label is "With Surfaces and DM". The goal of this test is to check if the DM can handle correcting the surface imperfections without losing too much stroke as well as remedy the 2 magnitude contrast drop from the open loop E2E test.

The pick-off location for the DM correction is at the Lyot stop because it is the last pupil plane before the coronagraphic PSF and detects most of the surface errors in the optics stream. POPPY calculates and returns the complex field at each propagation plane, so the pick-off plane is the phase generated at the Lyot stop (See Fig. 7a). The phase data is then moved to the Fourier domain, where the spatial frequencies the BMC2K DM cannot handle is filtered. The filtered data is returned to the phase domain where it is converted to OPD and inverted before being inserted as the correction surface map for the Tweeter DM (See Fig. 7b). The whole system is ran again from the start with the correction DM map in place. A single iteration of this correction reduced the Lyot plane phase RMS error from 1.104 rad to 0.1696 rad (See Fig. 7c). The DH contrast for the single iteration closed loop correction improves to  $6.16e^{-5}$  (see Fig. 6c), which is a whole magnitude of improvement from the open loop E2E analysis with surfaces. This contrast is considered as the MagAO-X DH contrast characterization.

## 3.3 Verification of Optical Element Specifications

A second analysis performed was to verify the optical element specifications for the MagAO-X testbed. While the DH contrast characterization tests performed in Sec. 3.2 showed that the optical element specifications can

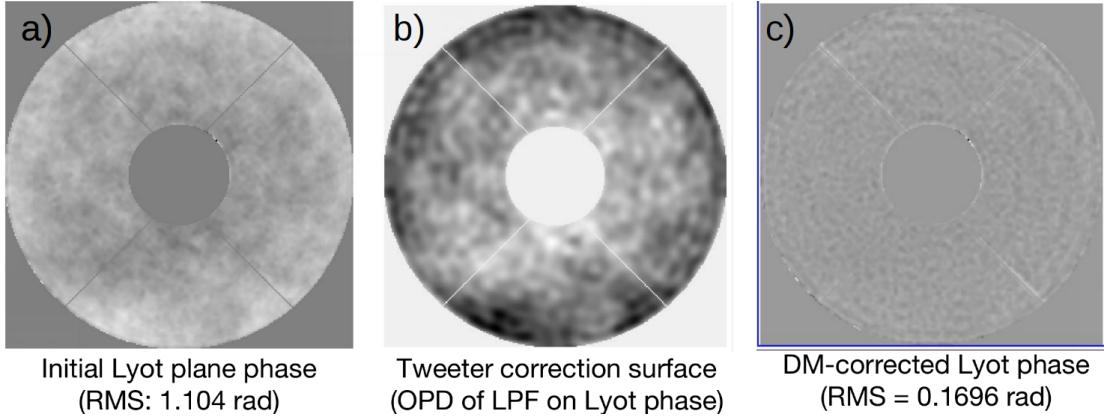


Figure 7. DM correction surfaces used for MagAO-X closed-loop E2E Fresnel propagation.

sufficiently produce a DH, the next goal is examining if there are any individual optical element(s) that affect the DH contrast. We perform this task to assure that the optical elements procured will be arranged in an optimal manner on the MagAO-X testbed.

For this test, the analyzed optical element has its surface removed from the system to simulate an unaberrated surface while all the other optical elements' surfaces remain the same. The tested optical element prescription remains the same, so there is no change in the testbed design. Replacing the tested optical element surface will show the diffraction effect produced by the optical element's surface onto the DH contrast. A DH contrast is generated for the removed optical element surface and repeated across each of the 23 optical elements. Additionally, this process is repeated using 5 PSD sets where the DH contrast is averaged across each set per tested optical element surface.

The results of the individual optical element surface test is featured in Fig. 8. The red horizontal line is the baseline reference DH contrast averaged across the tests where no optical element surfaces were removed (therefore labelled "noneRemoved"). The light blue box is the 1 standard deviation regime produced by the noneRemoved reference. Each tested optical element surface average DH contrast that lies inside the light blue box show that it performs on par with the noneRemoved reference. Therefore, the optical surface quality for that optical element is verified to meet performance.

However, it was found that when OAP7 is replaced with a perfect surface, the DH contrast performance alters beyond 1 standard deviation of the noneRemoved reference. This shows that the surface quality of OAP7 will have a critical impact on the MagAO-X system performance. One reason explaining this phenomenon is that OAP7's surface is invisible from the DM correction algorithm because it is positioned after the Lyot plane pick-off. A simple solution to this problem is to insert the best surface quality OAP for OAP7 when the MagAO-X testbed is being assembled.

#### 4. SPACE: LASER GUIDE STAR FOR LARGE APERTURE SEGMENTED SPACE TELESCOPES

The goal of the LGS demonstration testbed's Fresnel propagation simulation is to have an easily adjustable model to explore parameters, limits, and trade-offs on designing and characterizing the LGS demonstration testbed. This in turn will affect the LGS mission parameters being designed by the Massachusetts Institute of Technology STAR Laboratory. The model described in Sec. 4.1 is the current preliminary design model. Sec. 4.2 features the LGS correction procedure and preliminary results of the Fresnel propagation for the testbed design model described here.

##### 4.1 LGS Demonstration Testbed Model Description

The LGS demonstration testbed is a single pupil relay system. Fig. 9 features the testbed at the University of Arizona Extreme Wavefront Control Laboratory and a ZEMAX optical design model. It has two fiber point

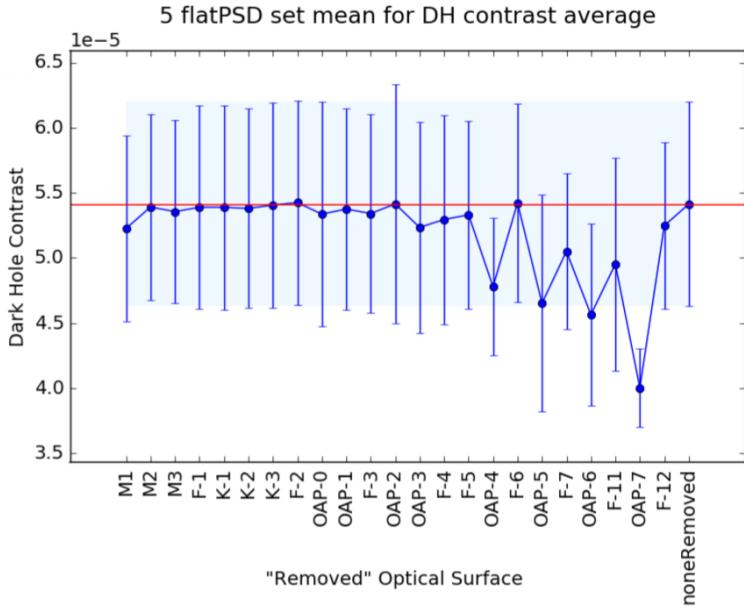


Figure 8. MagAO-X verification of optical element specifications test. Each optic was tested to see its individual contribution to the DH contrast.

sources to act as the on-axis target star and an off-axis LGS source. The wavelengths used are 531nm for the target star and a HeNe for the LGS. We are using an IrisAO PTT-111L segmented DM at the first pupil plane to represent LUVOIR. There is a 7mm inscribed aperture placed at the DM. A pellicle is placed before the first focal plane, where one path leads to a camera to image the on-axis source. The other is the WFS path, where a Zernike WFS (ZWFS) is placed at the focal plane of the off-axis LGS rays. An imaging lens is placed between the ZWFS to image the filtered segmented DM pupil.

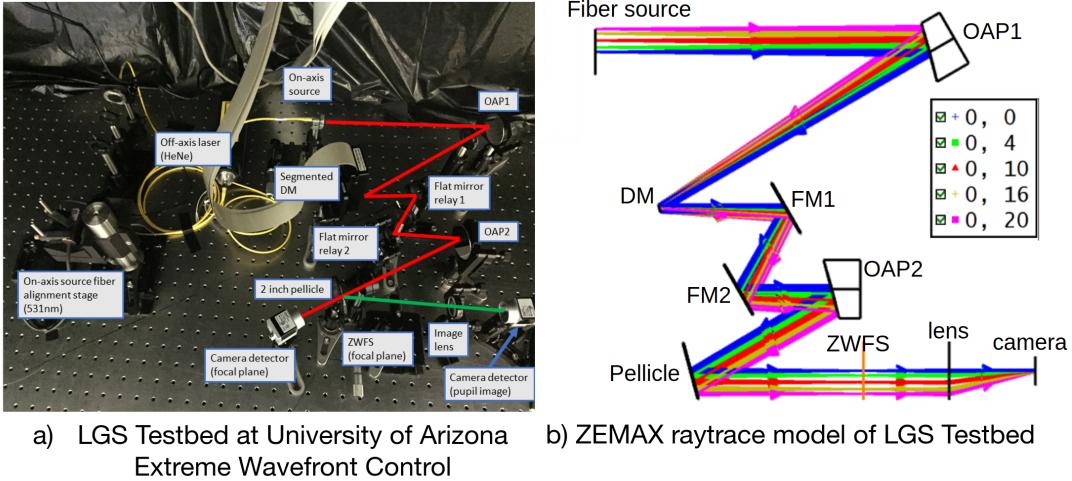


Figure 9. LGS demonstration testbed (preliminary design) at University of Arizona Extreme Wavefront Control Laboratory. The off-axis source will be fed into the system using a beamsplitter cube in future designs.

The on-axis source is a static and unaberrated, similar to MagAO-X. The off-axis source was modelled in POPPY using a ZWFE with tilt and defocus prescribed. The tilt value is based on the number of waves seen by

LUVOIR for a 10" off-axis source. The defocus value is based on the LGS cubesat placed 50,000 km away from LUVOIR.

Unlike the MagAO-X Fresnel propagation simulation which had optical element surface maps, the LGS simulation presented here does not include surface maps for the OAPs and flat mirrors. This will be implemented into future LGS Fresnel simulations. The only surface maps used in the LGS simulation are the ZWFS OPD map and the generated aberrations and corrections for the DM. To aberrate the segmented primary mirror, a ZWFE with 0.5 waves of astigmatism was induced on-axis. The aberrated primary mirror map is set as an OPD surface map and is calculated based on the on-axis wavelength.

## 4.2 Preliminary Results of LGS Demonstration Testbed

A single iteration closed-loop using the LGS source to correct the aberrated segmented primary mirror is described here. The on-axis aberrated segmented DM to correct is shown in Fig. 10a. Running the Fresnel propagation simulation produces the on-axis PSF in Fig. 10b.

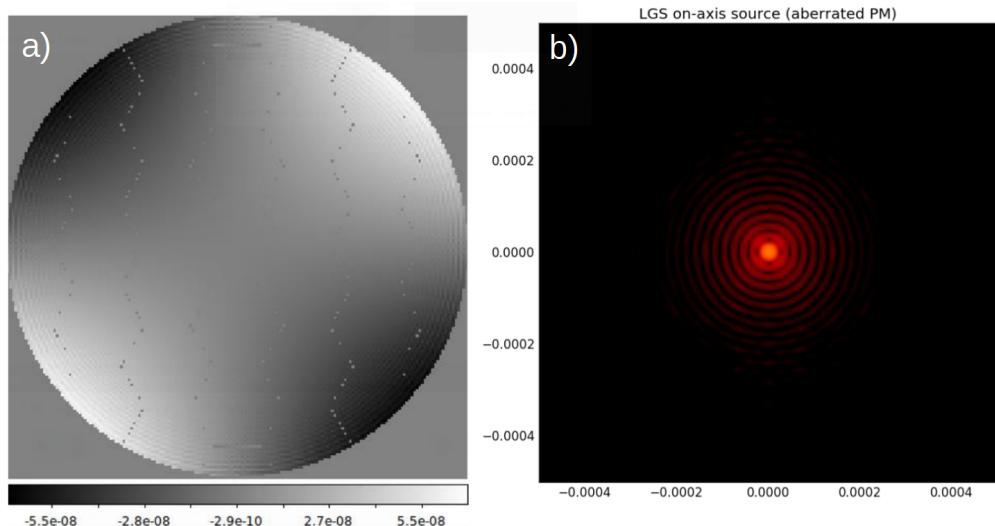


Figure 10. Initial test setup for LGS correction. a) Aberrated segmented DM for on-axis source. This is masked by the 7mm inscribed aperture on the IrisAO PTT-111L. b) Resulting PSF produced by aberrated segmented DM.

The LGS path follows from the ZWFE source and through the ZWFS route. The aberrated DM seen by the LGS is the OPD surface map generated by the on-axis source. The ZWFS image plane phase map seen by the LGS with the aberrated DM is shown in Fig. 11a. To correct the on-axis aberrated segmented DM, the ZWFS image plane phase map needs to remove the phase map contributed by the LGS itself. The LGS calibration phase map is produced by propagating the LGS through the system assuming a flat segmented DM and is shown in Fig. 11b. Once the LGS calibration phase map has been subtracted out of the ZWFS image plane phase map (see Fig. 11c), then these phases are inverted and converted to an OPD surface map.

The correction surface map is stacked onto the original aberrated segmented DM surface map, as shown in Fig. 12a. This whole process repeats again with the on-axis source route, and produces the PSF in Fig. 12b. The first iteration closed loop correction using the LGS shows a small level of correction. Qualitatively, the PSF core is cleaned up from the original aberrated DM on-axis PSF in Fig. 12b. Additionally, there is higher order ringing in the corrected PSF. This shows that the LGS on a basic level can help correct an aberrated segmented primary aperture. However, since this was done on a single iteration closed loop and the aberration applied to the DM is low order, additional iterations are required.

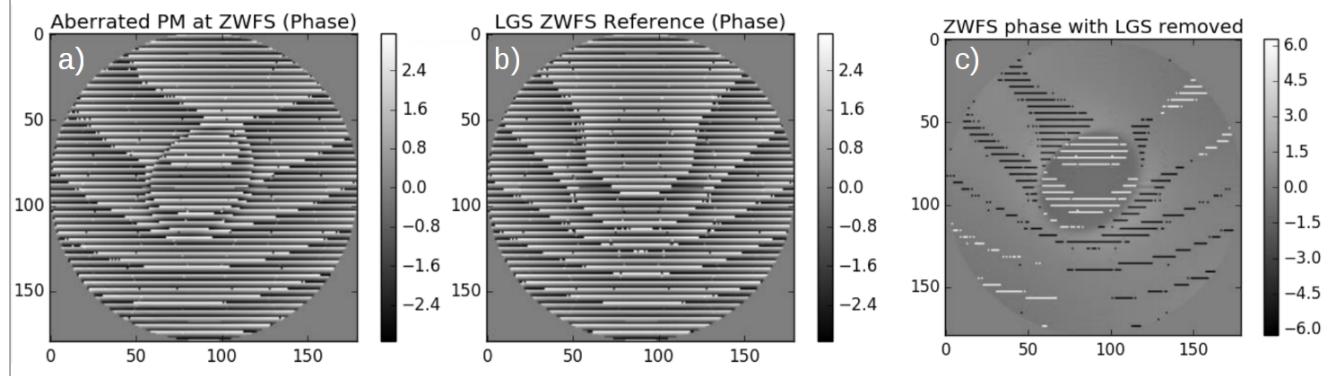


Figure 11. ZWFS pupil image phase maps. Each phase map is generated under different configurations: a) ZWFS pupil image phase seen by LGS with aberrated DM; b) ZWFS pupil image phase generated by the LGS with a flat DM, considered as the calibration phase to remove prior to correction; c) ZWFS pupil image phase of aberrated DM with LGS calibration phase removed.

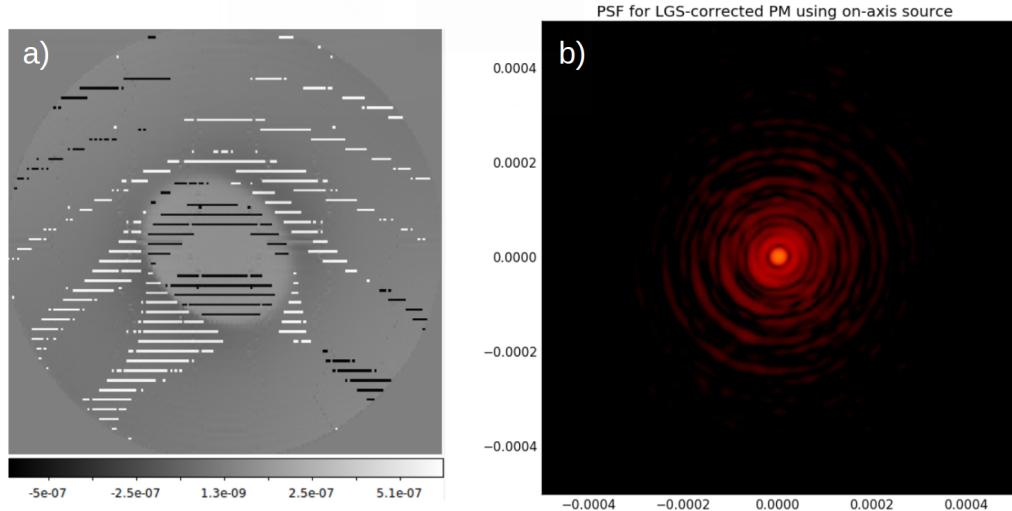


Figure 12. LGS-correction of on-axis aberrated DM. a) Superposition of original aberrated DM surface map with LGS correction surface map. b) Resulting on-axis source PSF from first iteration correction loop by LGS.

## 5. CONCLUSION AND FUTURE WORK

We showed that through an E2E simulation of the MagAO-X instrument that MagAO-X is capable of delivering visible-light high contrast imaging at  $6.16^{-5}$  limited by static, non-common path aberrations at small angular separations ( $1\text{-}10 \lambda/D$ ,  $19\text{-}190$  mas). The optical elements surfaces are verified to meet the specification requirements for DH generation. The MagAO-X optical elements have been ordered and have recently been received at University of Arizona Steward Observatory. They are currently undergoing testing with a Zygo Verifire Fizeau interferometer in the University of Arizona Extreme Wavefront Control Laboratory. PSD profiles of these optical elements are currently underway for development and will be incorporated into the MagAO-X POPPY model. Once the PSD analysis has been completed, it will be incorporated as a module into POPPY. Additionally, a dust analysis studying the effect on the dark hole contrast is currently being planned.

We demonstrated that the LGS concept study is capable of correcting an aberrated segmented aperture through an E2E simulation of the preliminary design testbed. Future work with the LGS include multiple iterations of closed-loop correction. This will eventually converge for a more robust testbed model with the parameters and design trade-offs considered. Once the design has been finalized through the E2E simulation, it

will be assembled and tested in the University of Arizona Extreme Wavefront Control Laboratory. Laboratory results will be compared with the Fresnel simulation.

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