



## 5.3 Fresnel Analysis

Jennifer Lumbres, Ewan Douglas, Jared Males

### 1 Introduction

This section will show the Fresnel propagation analysis of the MagAO-X optical system design. The Fresnel analysis will show the diffraction generated by each optical element in the MagAO-X optical system. This section will describe the software used, how the system is built, and an analysis describing an aberrated and unaberrated version of the MagAO-X system.

### 2 Software Description: POPPY

The software used for Fresnel analysis is named POPPY, which stands for Physical Optics Propagation in PYthon. The POPPY source code may be obtained here (1) . 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.

### 3 Building MagAO-X in POPPY

In POPPY, the MagAO-X 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 (2). This process is repeated throughout the entire system, until the science detection plane. The MagAO-X design optical elements used in POPPY can be found in Section 5.1 and the distances between each optic were pulled from the MagAO-X Zemax model (see Section 2.1, pages 20-24). The MagAO-X POPPY model may be found here (3).

**3.1 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 (M-1, M-2, all OAPs) are treated as quadratic lenses with a focal length parameter. Detection planes (focal planes, cameras) and deformable mirrors are represented as scalar transmission locations. Flat mirrors are also set as scalar transmission, but only in the unaberrated case. Flat mirrors have a PSD surface applied in the aberrated case.

POPPY also allows the user to insert custom amplitude transmissive or OPD phase optical elements into the system, thereby letting the user induce aberration at their discretion. This custom optical element feature has been used throughout the MagAO-X design analysis for custom pupils, optical surface quality, and the vAPP coronagraph mask. These surfaces are applied when the optical element is declared in POPPY.

The optics specifications described in Section 5.1 were used to generate representative surfaces for the various optics in MagAO-X. The actual surface map of M1 was used. For the other optics, PSDs were generated with the appropriate parameters and normalization. See Fig. 1 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. See 5.1 for a complete description. The PSDs were used to generate surface maps by using standard Fourier convolution with Gaussian white noise.

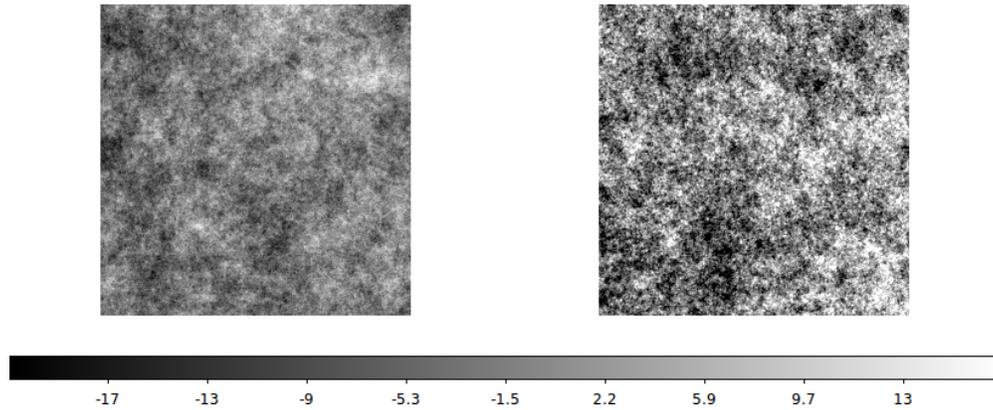


Figure 1: Sample MagAO-X optical surfaces used in POPPY (left: F-0 flat mirror; right: O-0 OAP mirror)

**3.2 System Build:** There are two different MagAO-X system builds analyzed in POPPY: an unaberrated case (POPPY's default perfect optics case) and an aberrated case (includes a surface PSD at each optical element). Both systems use the same unmasked pupil and vAPP coronagraph mask and are tested at 656 nm. More information about the POPPY modeling can be found in the A section. Once an optical system has been built into POPPY, it is possible to calculate the wavefront amplitude, phase, and intensity at each optical element. The aberrated and unaberrated cases are examined for both with and without the vAPP coronagraph present.

**3.2.1 MagAO-X without vAPP coronagraph:** To show the MagAO-X design performance, Figs. 2 - 6 present PSFs generated at each focal plane, both aberrated and unaberrated, without the vAPP coronagraph present. As the beam propagates through the system, the aberrated case shows the PSF rings gradually losing shape as more optics are encountered.

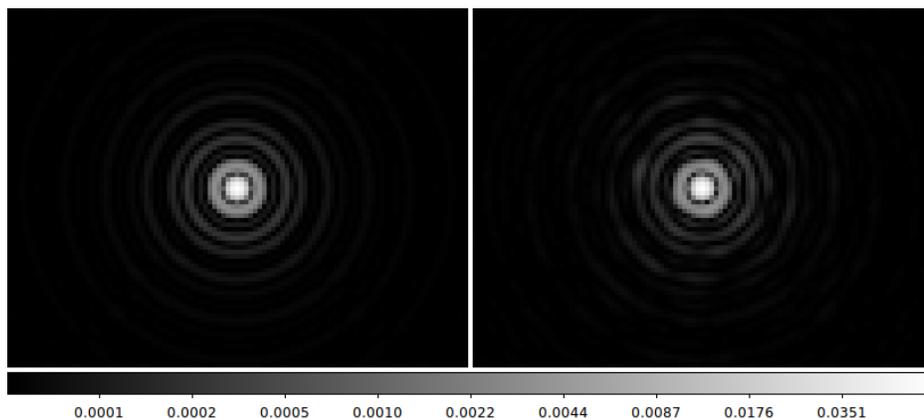


Figure 2: MagAO-X F/11 PSFs for unaberrated (left) and aberrated (right) systems

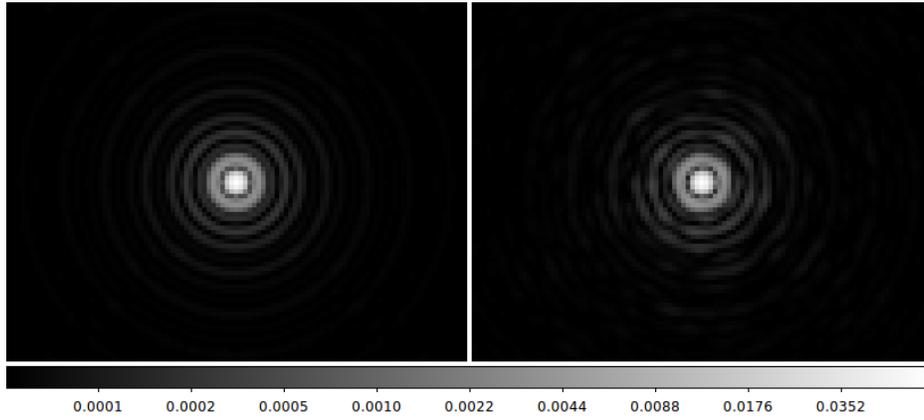


Figure 3: MagAO-X F/16 PSFs for unaberrated (left) and aberrated (right) systems

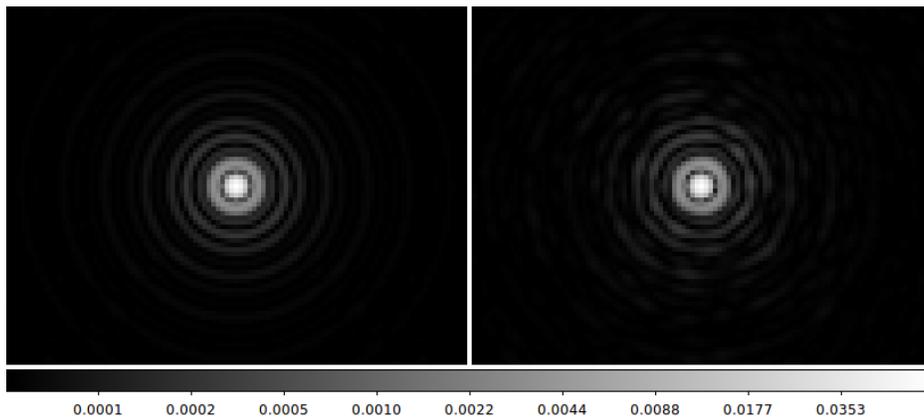


Figure 4: MagAO-X F/57 PSFs for unaberrated (left) and aberrated (right) systems

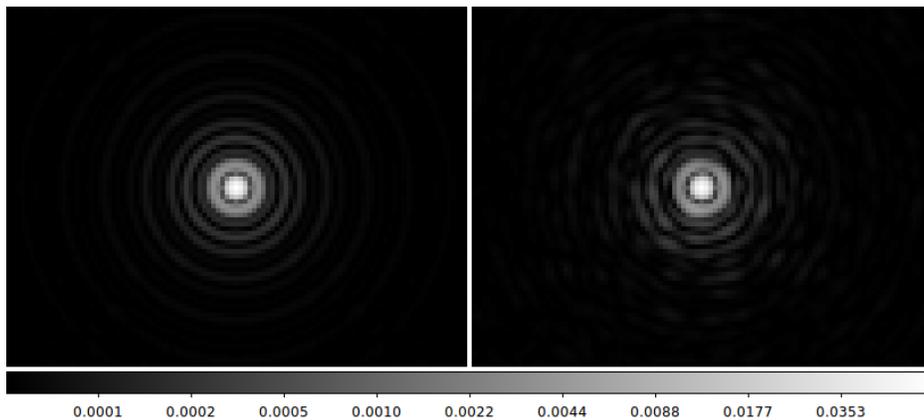


Figure 5: MagAO-X F/69 PSFs for unaberrated (left) and aberrated (right) systems

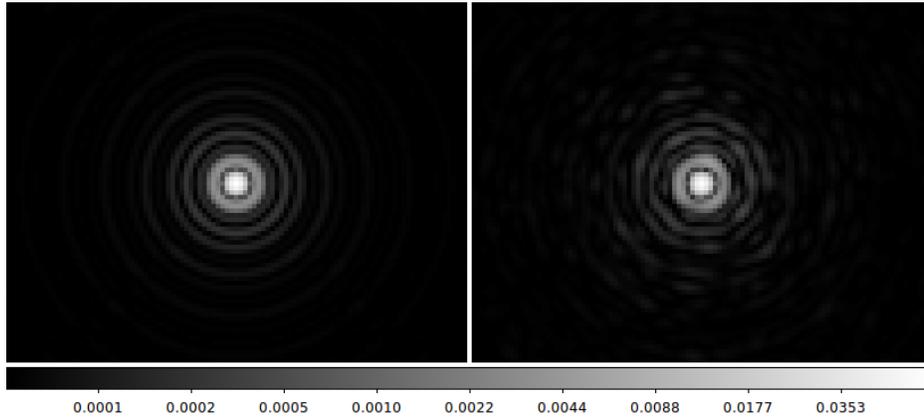


Figure 6: MagAO-X F/69 Science plane PSFs for un aberrated (left) and aberrated (right) systems

**3.2.2 MagAO-X with vAPP coronagraph:** The MagAO-X system was tested with the vAPP coronagraph present. The vAPP coronagraph used in POPPY is the phase pattern version (see Section 5.2 for more information regarding the vAPP coronagraph design). The intermediary focal planes will not be shown, as the performance remains the same from earlier. Fig. 7 compares the vAPP coronagraph F/69 science plane PSF performance between the un aberrated and aberrated cases. Both cases generate a dark hole on the left, however the aberrated case displays less contrast. This reduced contrast is caused by Fresnel effects generated from the optical elements post-coronagraph.

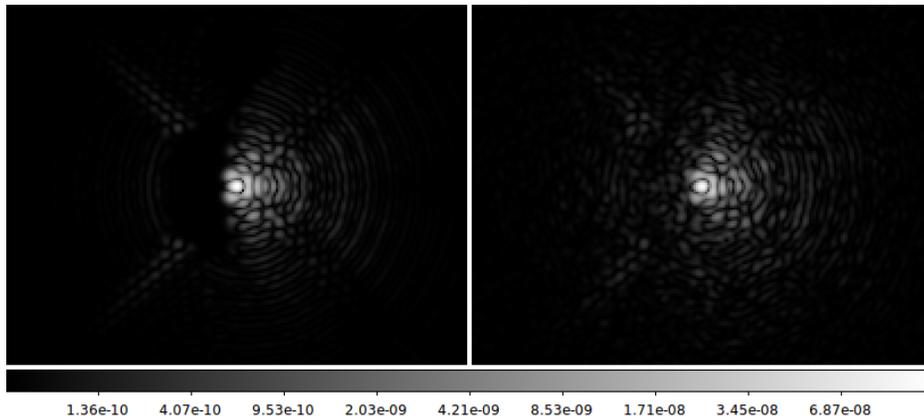


Figure 7: MagAO-X F/69 Science plane PSFs with vAPP coronagraph implemented, for un aberrated (left) and aberrated (right) systems

#### 4 vAPP Performance

Fig. 8 compares the vAPP contrast with and without the expected optical imperfections in the MagAO-X system. The black and red dashed lines show the design contrast of the vAPP phase mask, presented in section 5.2. The black dashed line is for simple Fraunhofer propagation through the vAPP, and the red dashed line is the output of our POPPY simulation with no aberrations. The solid red line is the vAPP contrast with the aberrations included



in the MagAO-X optics. The dot-dashed red line shows the case where Fresnel propagation through the aberrated optics is performed to the vAPP pupil plane, but Fraunhofer propagation is performed thereafter. This indicates that the optics downstream of the coronagraph apodizer plane are having a strong effect on post-coronagraph contrast due to Fresnel effects. Finally, we show in blue the residual halo from atmospheric turbulence in our end-to-end (E2E) simulations.

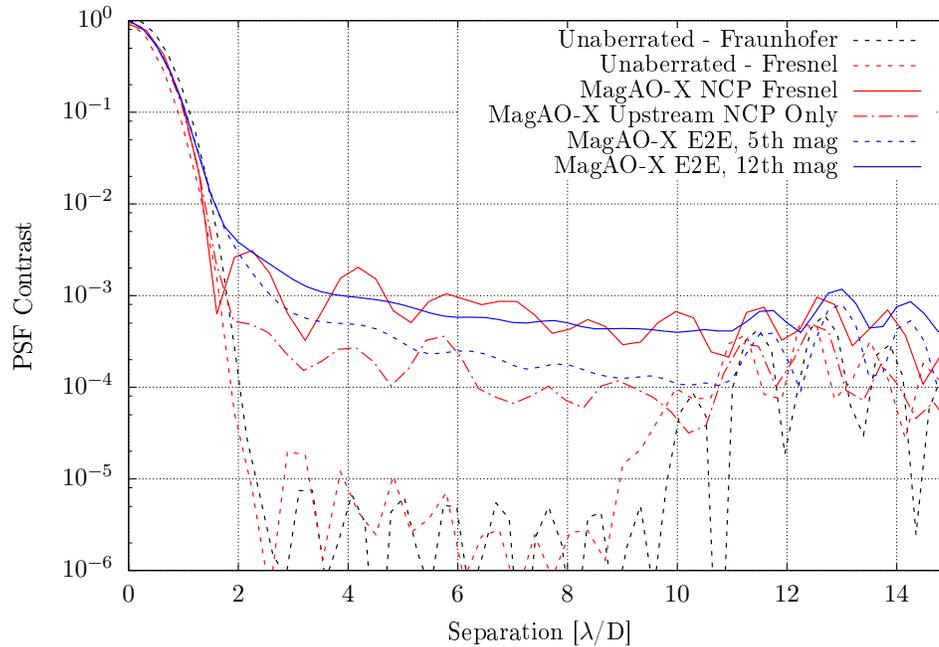


Figure 8: vAPP Performance in MagAO-X

### A POPPY program parameters

The POPPY project is a work in progress, so different versions may affect how the MagAO-X POPPY Fresnel analysis gets rendered. Here we will list various details and assumptions made in the analysis.

The following optical element assumptions were implemented in POPPY for both aberrated and unaberrated cases:

- No wavefront sensing feedback
- Perfect DM surfaces
- Perfect wavefront sensor at each intermediary focal plane and at F/69 science focal plane
- No amplitude alteration from optical surface PSD implemented

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

- POPPY version: 0.6.0rc



**MagAO-X Preliminary Design**  
**5.3: Fresnel Analysis**

Doc #:	MagAOX-001
Date:	2017-04-23
Status:	Rev. 0.0
Page:	6 of 6

- Date of POPPY download: January 17, 2017
- Git hash for MagAO-X aberrated model in POPPY: eb594df
- Git hash for MagAO-X unaberrated model in POPPY: 6be492b

**References**

- [1] M. Perrin, J. Long, E. Douglas, N. Zimmerman, A. Sivaramakrishnan, K. Douglass, and M. Grochowicz, “Physical optics propagation in python,” 2017.
- [2] G. Lawrence, “Optical modeling,” *Applied Optics and Optical Engineering* **XI**, p. 125, 1992.
- [3] J. Lumbres, “Magao-x poppy source,” 2017.