Post-Launch Optical Aberration Detection for Small Satellites

Spectral Ocean Color Imager (SPOC) and Multi-view Onboard Computational Imager (MOCI)

Kaitlyn Summey*[1], David L. Cotten^[1,2], Deepak Mishra[1,2]

*Kaitlyn.summey25@uga.edu, ^dcotte1@uga.edu, [1]Small Satellite Research Laboratory, University of Georgia, [2]Center for Geospatial Research, University of Georgia

UNIVERSITY OF GEORGIA

Overview:

Aberrations in the wavefront of the light traveling through an optical system directly affect image quality. Being able to measure the aberrations in the system make it possible to reduce image distortion during post-processing. Aberrations are inherent in any optical system, but they are often exacerbated by misalignments, such as those caused by vibrations of a fixed optical system during launch. Knowing these misalignments are unavoidable, the UGA Small Satellite Laboratory has devised a plan to compute the wavefront using images from our small satellites in orbit.

Traditionally, imaging systems that wish to perform wavefront sensing have an on-board sensor, but since space and mass are incredibly limited on small satellites, including a wavefront sensor is not always feasible. However, there are image based wavefront sensing techniques that can be implemented using only satellite imagery. We are proposing two potential methods to reconstruct an aberrated wavefront from small satellite data.

1. Phase retrieval
2. Image based reconstruction

Background:

Over the next few years, the University of Georgia Small Satellite Research Lab will be launching two cube satellites. Both of our missions will be imaging Earth's surface with fixed optical systems. Even though the optics on-board differ to support the goals of each mission, we are able to implement general wavefront reconstruction methods that can be used with the data from either mission.

With our optics being fixed, we are aware that the vibrations experienced during launch could lead to misalignments in our optical systems.

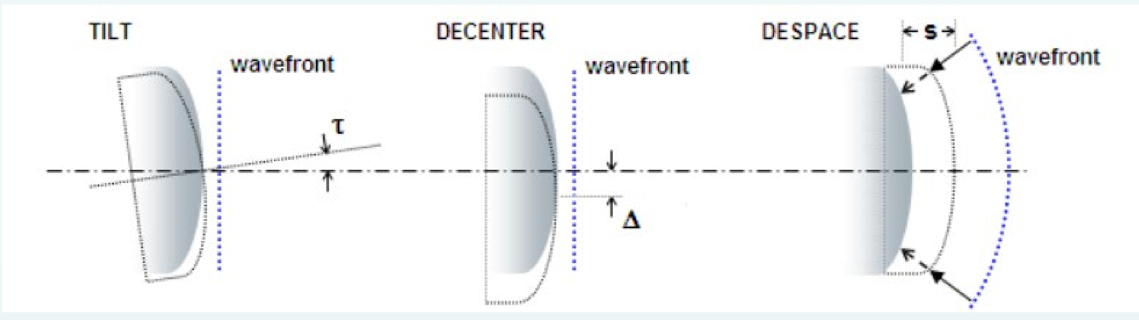


Figure 1: The wavefront effects of misalignments in lenses

There are also many other environmental factors, such as atmosphere and temperature, that can cause components in the system to shift. Our goal is to be able to characterize these optical aberrations and use the reconstructed wavefront for image processing.

Optical Aberrations:

In an ideal optical system, all of the light would travel through the system to be focused at a certain point, which is usually on a detector. Optical aberrations cause image distortion by spreading the light incoherently throughout an optical system.

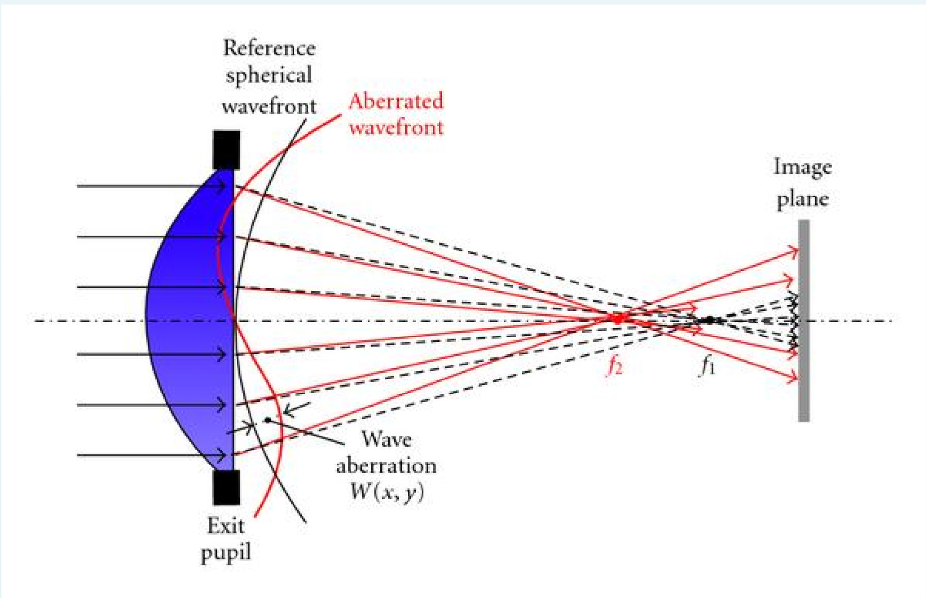
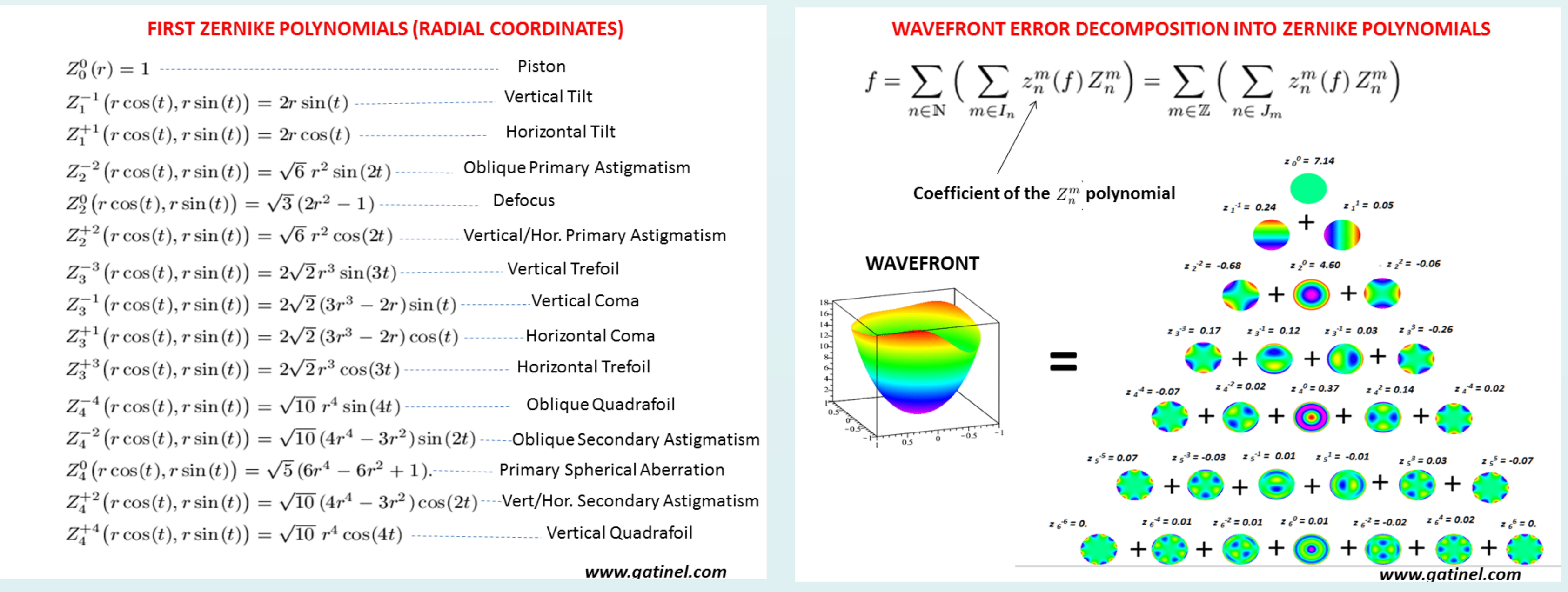


Figure 2: This diagram shows light traveling through a focusing lens with the ideal and aberrated wavefront shown along with the effects of the aberrations on the focusing of the light.

In addition to there being many causes of aberrations, there are also many types. Zernike polynomials are used to create 3D functions of optical aberrations. The lower-order Zernike polynomials are the least complex and most recognizable optical aberrations.



Point Spread Function:

The point spread function of an optical system is the system's intensity response to a point source of light. Since optical aberrations effect the way light travels in a system, these aberrations can be seen in the point spread function.

During image processing, we can use deconvolution to remove aberrations from our data.

$$\textit{Observed Image} = \textit{Image} * \textit{Point Spread Function} + \textit{noise}$$

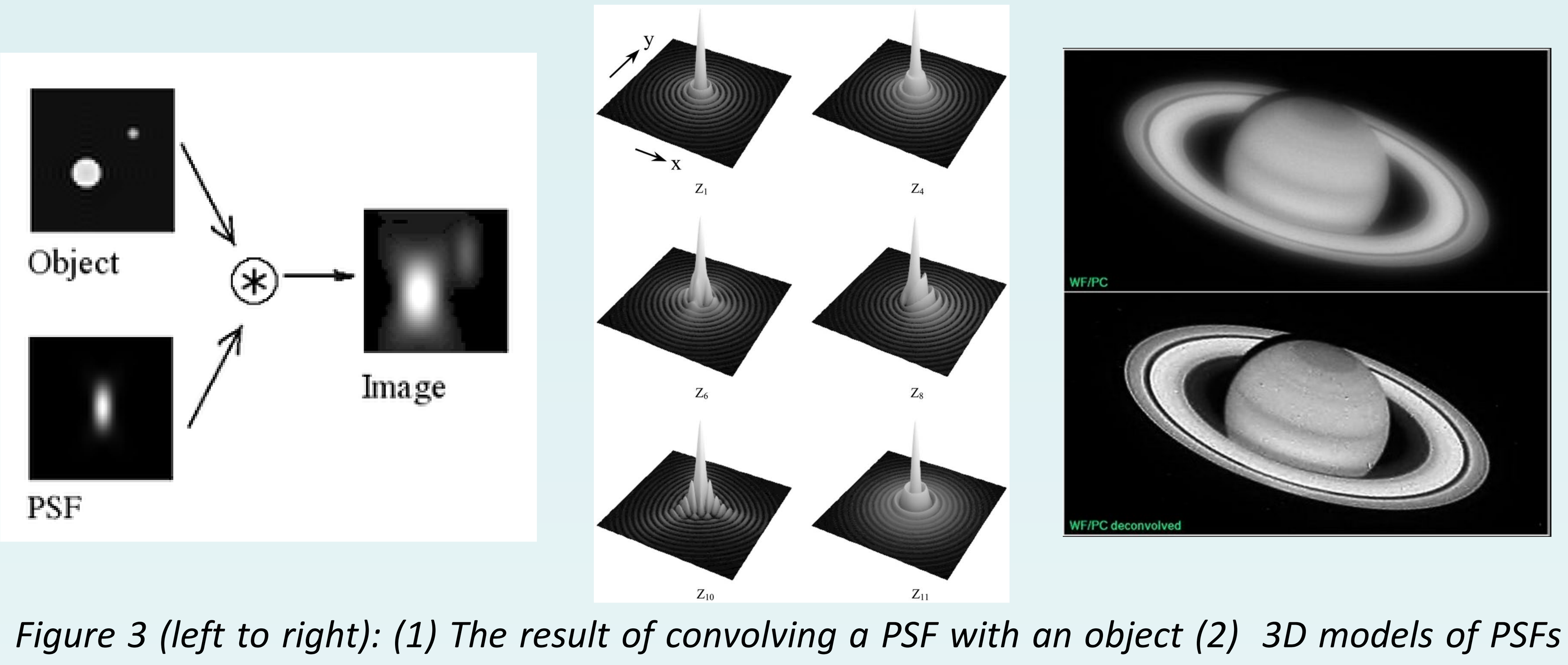


Figure 3 (left to right): (1) The result of convolving a PSF with an object (2) 3D models of PSFs with varying optical aberrations (3) The result of deconvolution in image processing

Methods:

1. Phase Retrieval

We can use a phase retrieval algorithm to compute the wavefront based on the intensity data from our images through the optimization of Zernike coefficients. A model is randomly instantiated with Zernike coefficients and a PSF is generated. These coefficients are optimized via gradient decent by comparing the generated PSF to the observed PSF.

The complication with performing phase retrieval on small satellite data is the resolution. Most small satellites do not have the imaging or control capability to be able to use a guide star as a point source. Using known optical function relations, we can image an edge, such as Earth's horizon or the boundary of a large city, to obtain the edge spread function. From there, we can derive the point spread function.

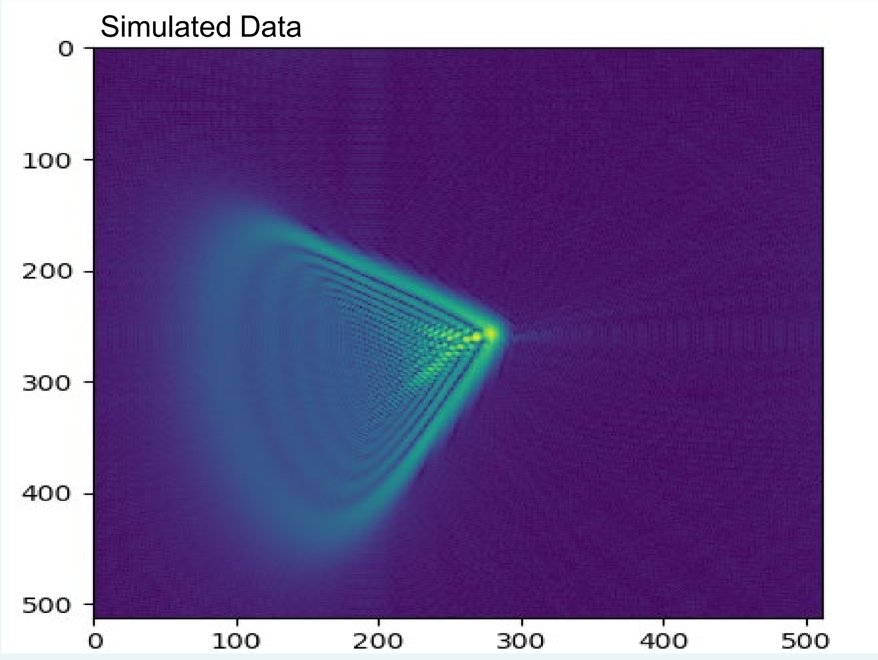
$$e(x) = \int_{x'}^{+\infty} l(x')dx' \qquad l(x') = \int_{-\infty}^{+\infty} p(x', -y)dy$$

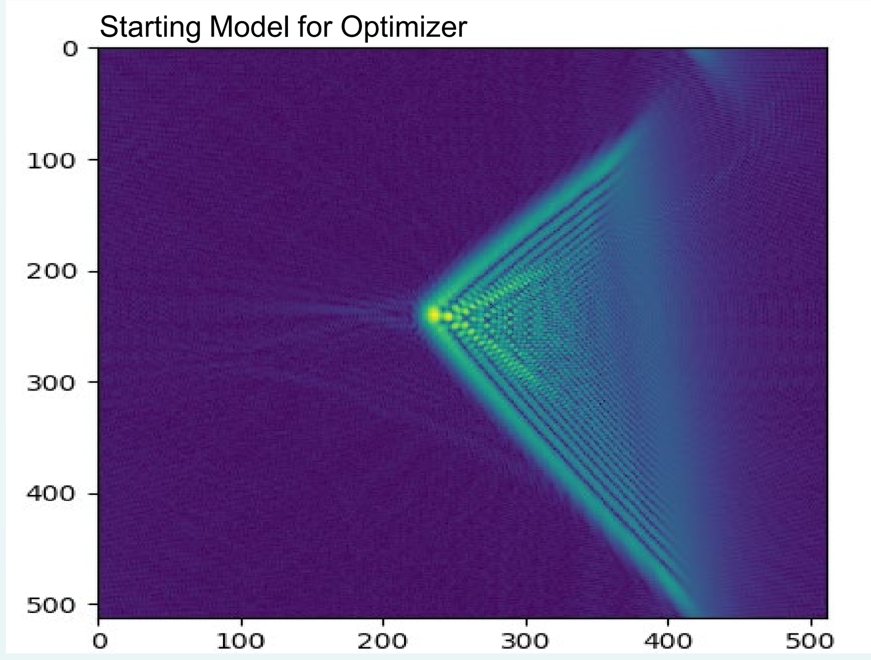
Figure 4: (a) The edge spread function, e(x) is the integral of the line spread function, l(x). (b) The line spread function is t integral of the point spread function

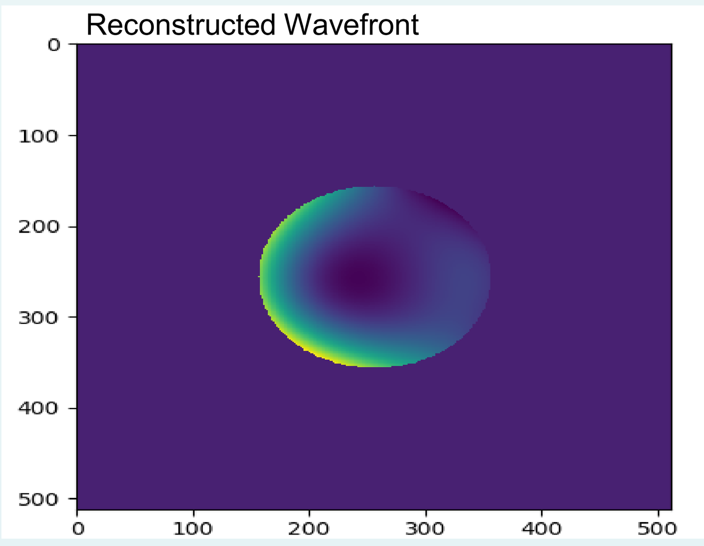
2. Image Based Reconstruction

Since many of NASA's Earth science satellite's data is open source, we can use their data as a "known truth" and reconstruct the wavefront by comparing the two sets of data. Since an image is the result of the convolution of the aberrated point spread function with the true object, we can algorithmically determine the point spread function of our system.

Results & Conclusion:

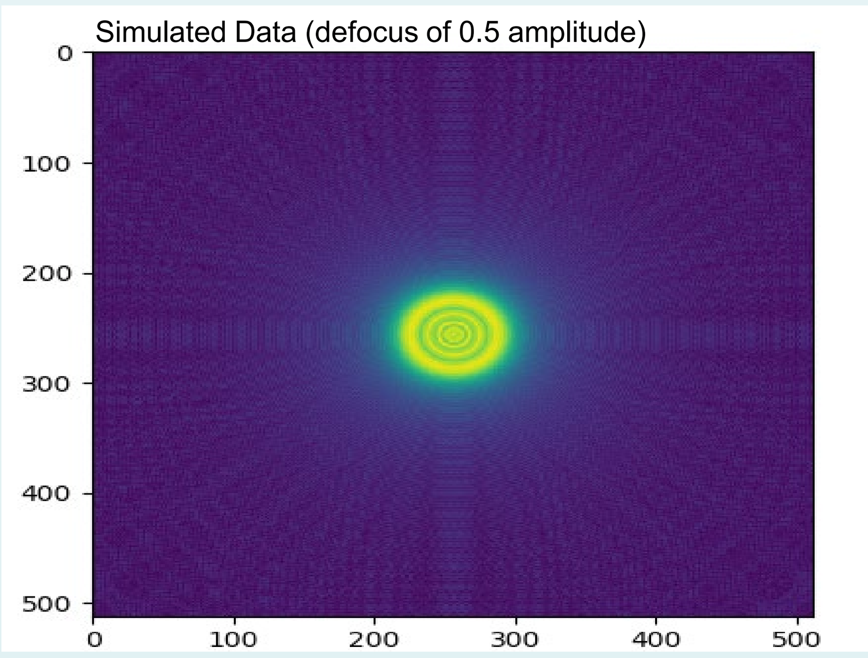


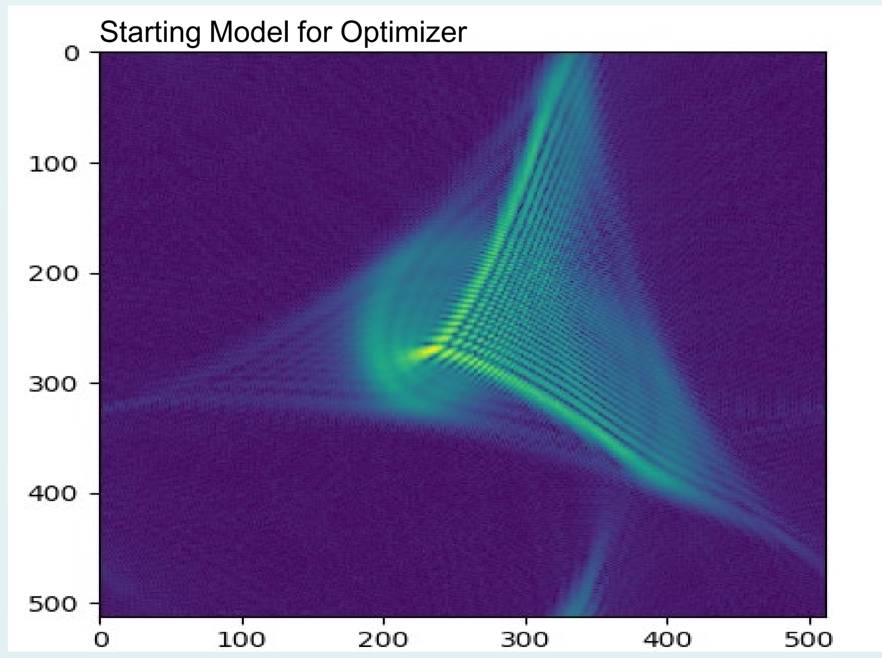


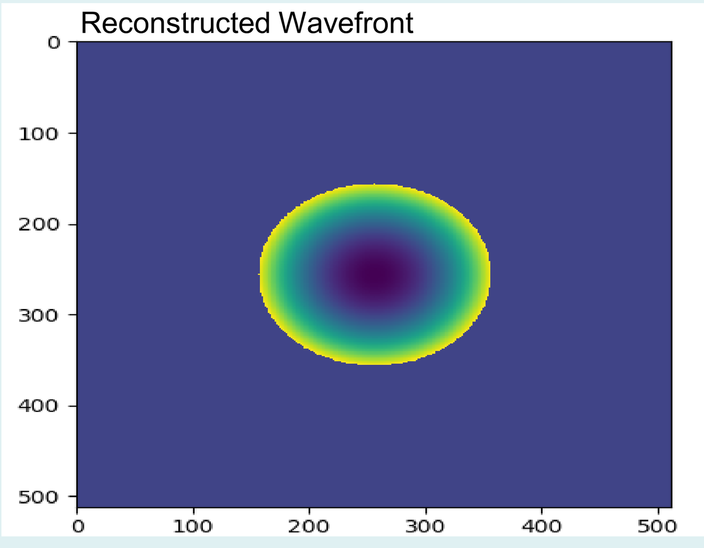



```
[-0.275 -0.084 -0.264  0.363  1.     0.472  0.411  0.394  0.098  0.047]
[ 0.474 -0.012  0.265  0.049  1.     0.047 -0.156 -0.319  0.119  0.106]
      fun: 0.0
 hess_inv: <10x10 LbfgsInvHessProduct with dtype=float64>
      jac: array([0., 0., 0., 0., 0., 0., 0., 0., 0., 0.])
  message: b'CONVERGENCE: NORM_OF_PROJECTED_GRADIENT_<=_PGTOL'
     nfev: 1
      nit: 0
   status: 0
  success: True
        x: array([ 0.474, -0.012,  0.265,  0.049,  1.   ,  0.047, -0.156, -0.319,
        0.119,  0.106])
```

The terminal output from the phase retrieval algorithm. The first printed array is the random starting Zernike coefficients (starting model above), followed by the final coefficients after optimization.








```
[ 0.149  0.073  0.341  0.039  1.     0.087  0.418  0.208 -0.156 -0.48 ]
[0.  0.  0.  0.  0.5 0.  0.  0.  0.  0. ]
      fun: 0.0
 hess_inv: <10x10 LbfgsInvHessProduct with dtype=float64>
      jac: array([0., 0., 0., 0., 0., 0., 0., 0., 0., 0.])
  message: b'CONVERGENCE: NORM_OF_PROJECTED_GRADIENT_<=_PGTOL'
     nfev: 1
      nit: 0
   status: 0
  success: True
        x: array([0. , 0. , 0. , 0. , 0.5, 0. , 0. , 0. , 0. , 0. ])
```

The terminal output from the phase retrieval algorithm. The first printed array is the random starting Zernike Coefficients, followed by the final values. This simulation shows a PSF and wavefront with only defocus applied.

The simulations and results above show that we are able to reconstruct a wavefront based on the point spread function. The next steps will be to develop algorithms to derive the point spread function from the various types of data that was discussed.

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