Numerically Optimized Coronagraph Designs for the HabEx Mission Concept

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Outline

1. HabEx Mission Concept Overview
   a) Goals
   b) Architecture
   c) Baselined coronagraph
   d) Goals of study

2. Numerical Design Strategy
   a) 1-D Radial Coronagraph Design
   b) Design Strategy
   c) HLC Design

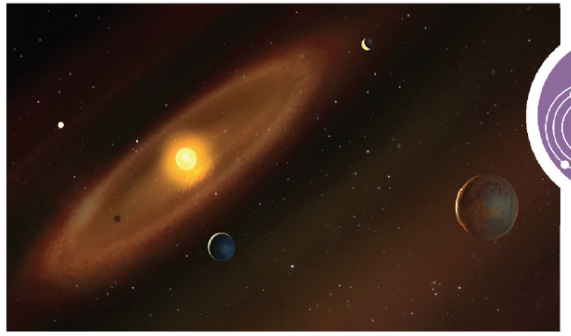
3. Summary & Future Work

Purpose of HabEx

EXPLORING PLANETARY SYSTEMS** AROUND NEARBY SUNLIKE STARS AND ENABLING OBSERVATORY SCIENCE FROM THE UV THROUGH **NEAR-IR

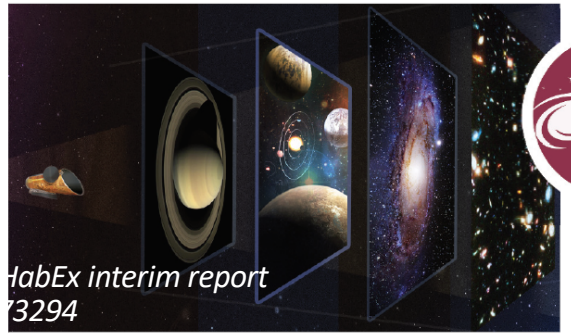
GOAL 1

To seek out nearby worlds and explore their habitability, *HabEx* will search for habitable zone Earth-like planets around sunlike stars using direct imaging and will spectrally characterize promising candidates for signs of habitability and life.



GOAL 2

To map out nearby planetary systems and understand the diversity of the worlds they contain, *HabEx* will take the first "family portraits" of nearby planetary systems, detecting and characterizing both inner and outer planets, as well as searching for dust and debris disks.



GOAL 3

To carry out observations that open up new windows on the universe from the UV through near-IR, *HabEx* will have a community driven, competed Guest Observer program to undertake revolutionary science with a large-aperture, ultra-stable UV through near-IR space telescope.

from HabEx interim report URS273294

Engineering Goals for Coronagraph:

1. Inner working angle ~ 2-2.5 λ/D
2. High off-axis throughput
3. <=1e-10 raw contrast
4. 20% spectral bandwidth
5. Robustness to tip/tilt other low-order Zernike aberrations

HabEx Architecture A Concept

- The HabEx STDT chose these parameters for Architecture A:
  - Telescope with a 4m aperture
  - 72-m diameter, formation flying external Starshade occulter
  - Four instruments:
    - **Coronagraph Instrument** for Exoplanet Imaging
    - Starshade Instrument for Exoplanet Imaging
    - UV– Near-IR Imaging Multi-object Slit Spectrograph for General Observatory Science
    - High Resolution UV Spectrograph for General Observatory Science

Image from HabEx interim report URS273294

Baselined Coronagraph

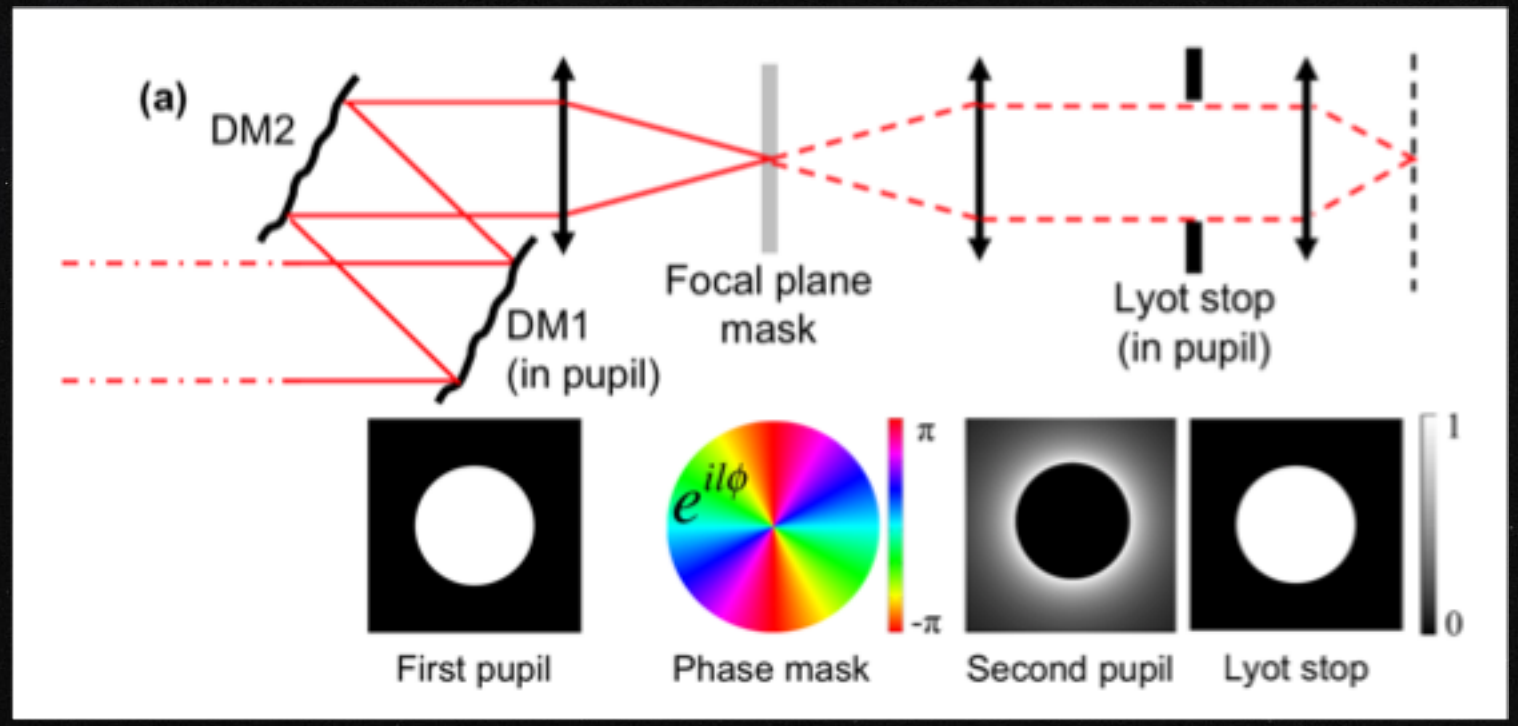


Figure from G. Ruane, "Vortex coronagraphs for the HabEx Mission Concept", JATIS, 2018.

Vector vortex coronagraph (VVC) is baselined for HabEx

- **Charge 6** vortex chosen for best balance between performance and robustness to low-order aberrations

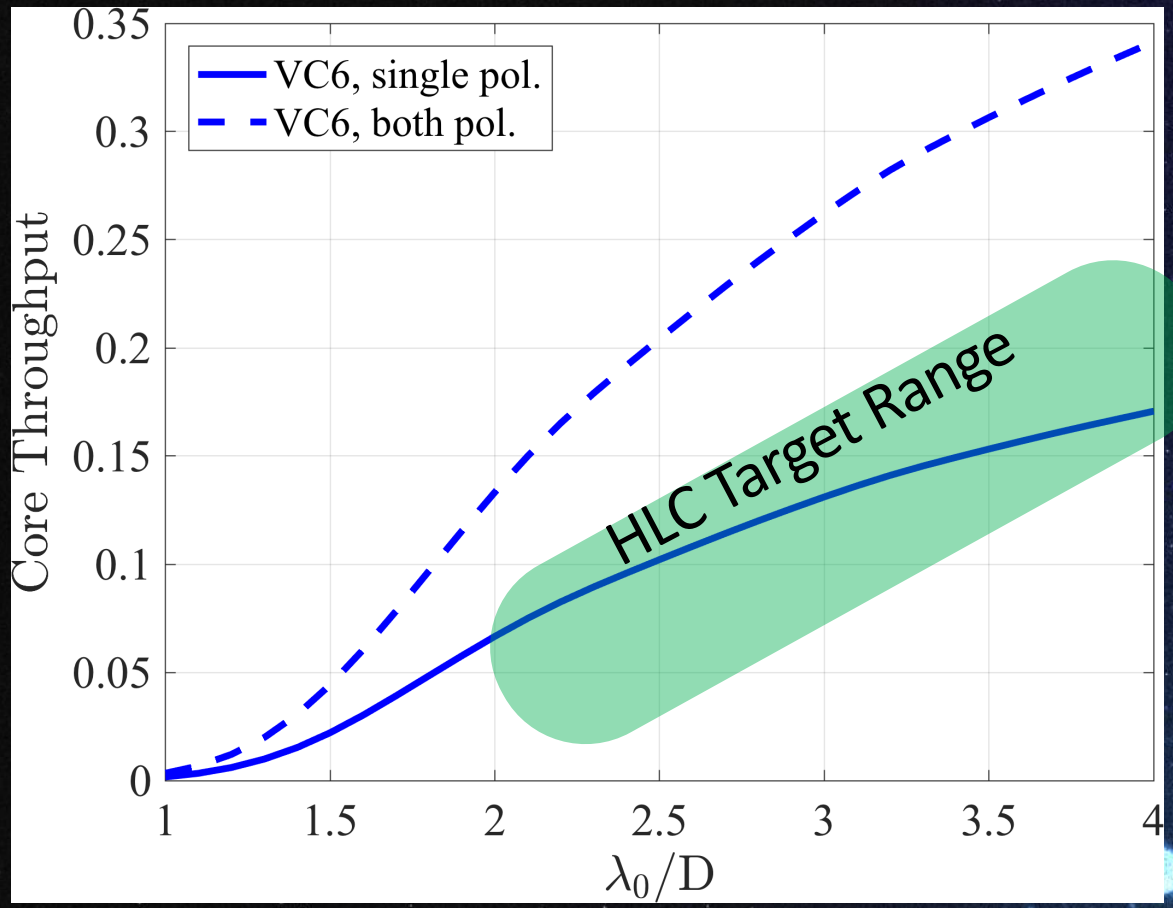
This Design Study

Goals:

1. Investigate **heritage** (TRL 5) coronagraphs from WFIRST CGI for HabEx
   a) Shaped pupil coronagraph (**SPC**)
   b) Hybrid Lyot coronagraph (HLC)
2. Compare performance to baselined VVC charge 6.

Performance Targets for Science Goals:

1. **High throughput at small working angles** (2-4 lambda/D) for exo-Earth detection
2. Largest possible dark hole (set by # of DM actuators) for planetary systems



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Benefits of 1-D Radial Design

1. Correct for circular/annular pupils
   - Is a true 2-D solution (just azimuthally symmetric)

2. **Speed**! Orders of magnitude faster
   a) **Comprehensive** grid searches
   b) Investigate **many different methods**
   c) Fast results even for **nonlinear** sub-programs

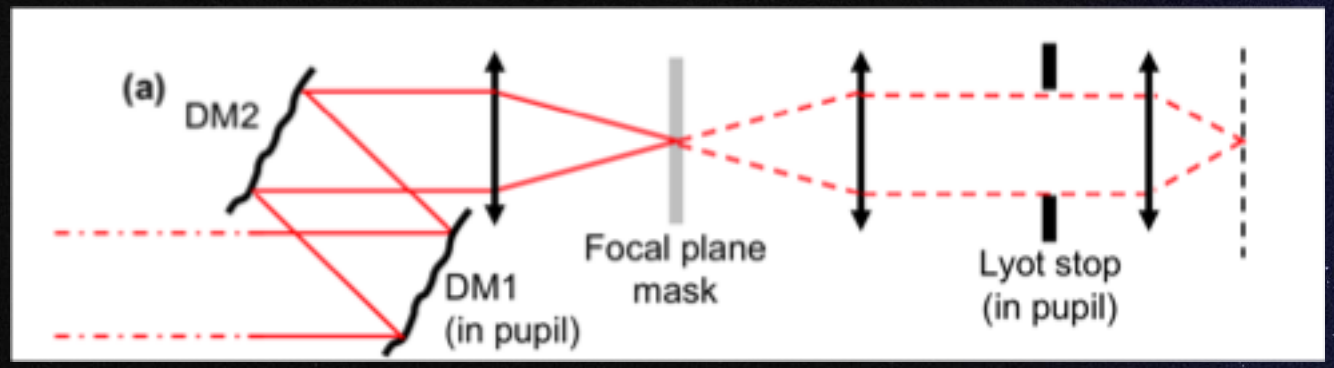
3. Can easily represent Zernike polynomials in 1-D
   a) Simply change the order of Hankel transforms
   b) Directly suppress sensitivities to low-order Zernike modes (from finite stellar size, thermal variations, etc)

Design Strategy

Optimization Problem:

Find the "best" configuration using

a) two DM surfaces
b) complex-amplitude FPM
c) Lyot stop



➢ *Nonlinear, nonconvex problem*

DM = deformable mirror
FPM = focal plane mask

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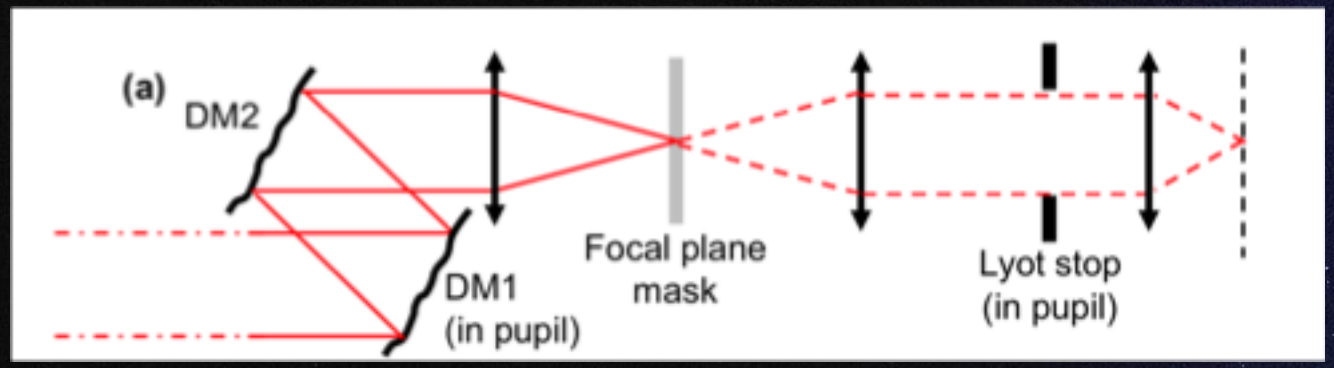


➢ *Nonlinear, nonconvex problem*

How to solve?

a) Break into smaller, tractable steps.
b) Test strategies in 1-D coordinates first.

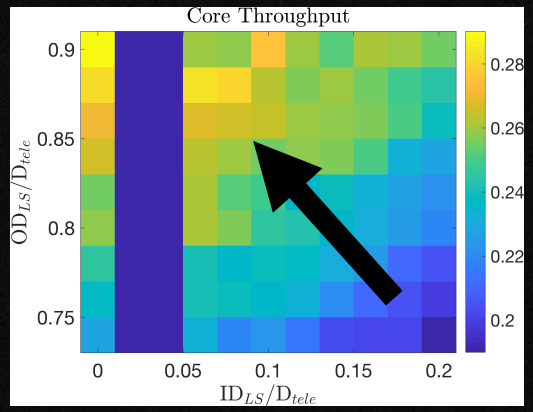
DM = deformable mirror
FPM = focal plane mask

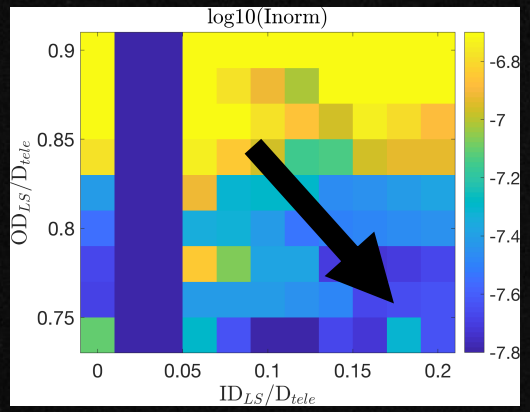
HLC Design (1/3)

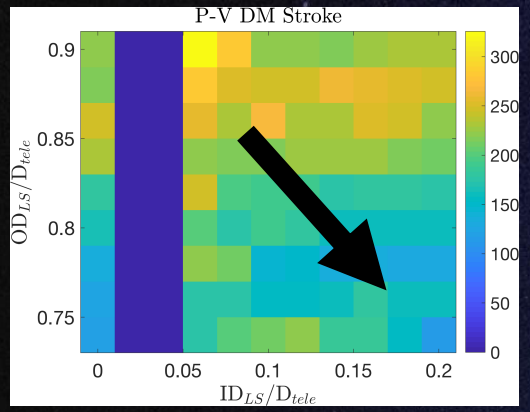
Step 1:

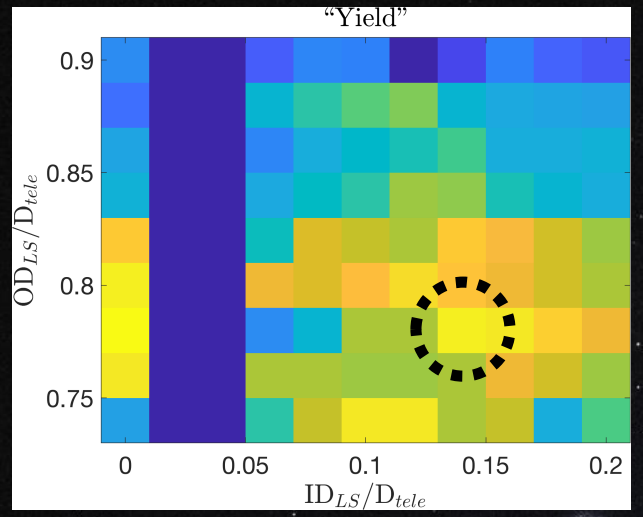
1-D DMLC survey to find good mask parameters:

1. Lyot stop ID
2. Lyot stop OD
3. FPM radius









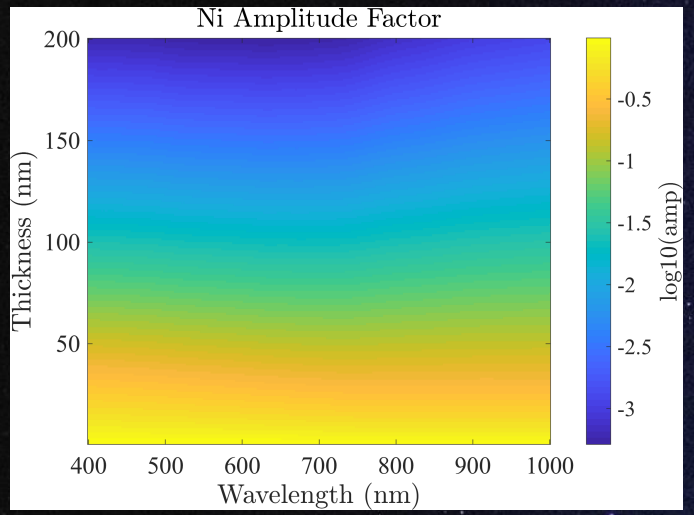
DM = deformable mirror
LC = Lyot coronagraph
ID = inner diameter
OD =outer diameter
FPM = focal plane mask

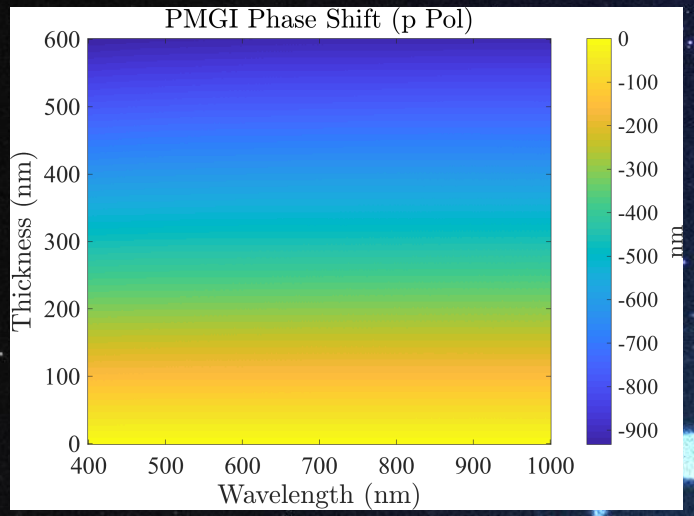
HLC Design Survey (2/3)

Steps 2+: Optimize the FPM (and DMs)

a) Optimize metal and dielectric layers
- 1st order approximation:
  i. amplitude = $\log_{10}$(metal thickness)
  ii. phase delay = -(dielectric thickness)/λ

b) Concurrently optimize FPM and DM shapes
- *Two wrongs make a right:*
  Chromaticity of DMs and FPM offset



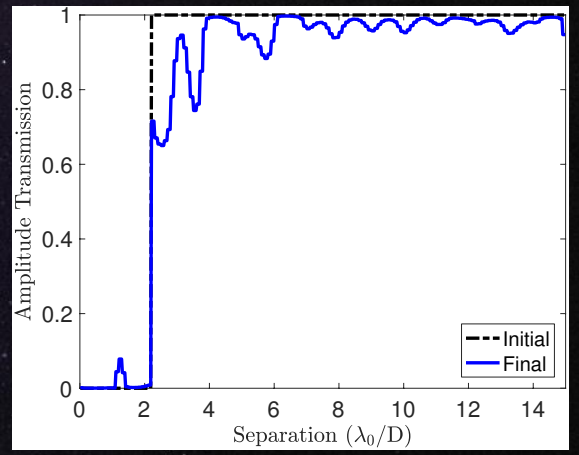


DM = deformable mirror
FPM = focal plane mask

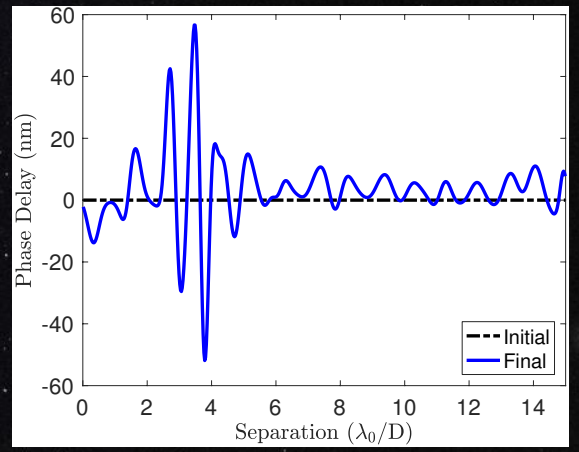
HLC Design Survey (3/3)

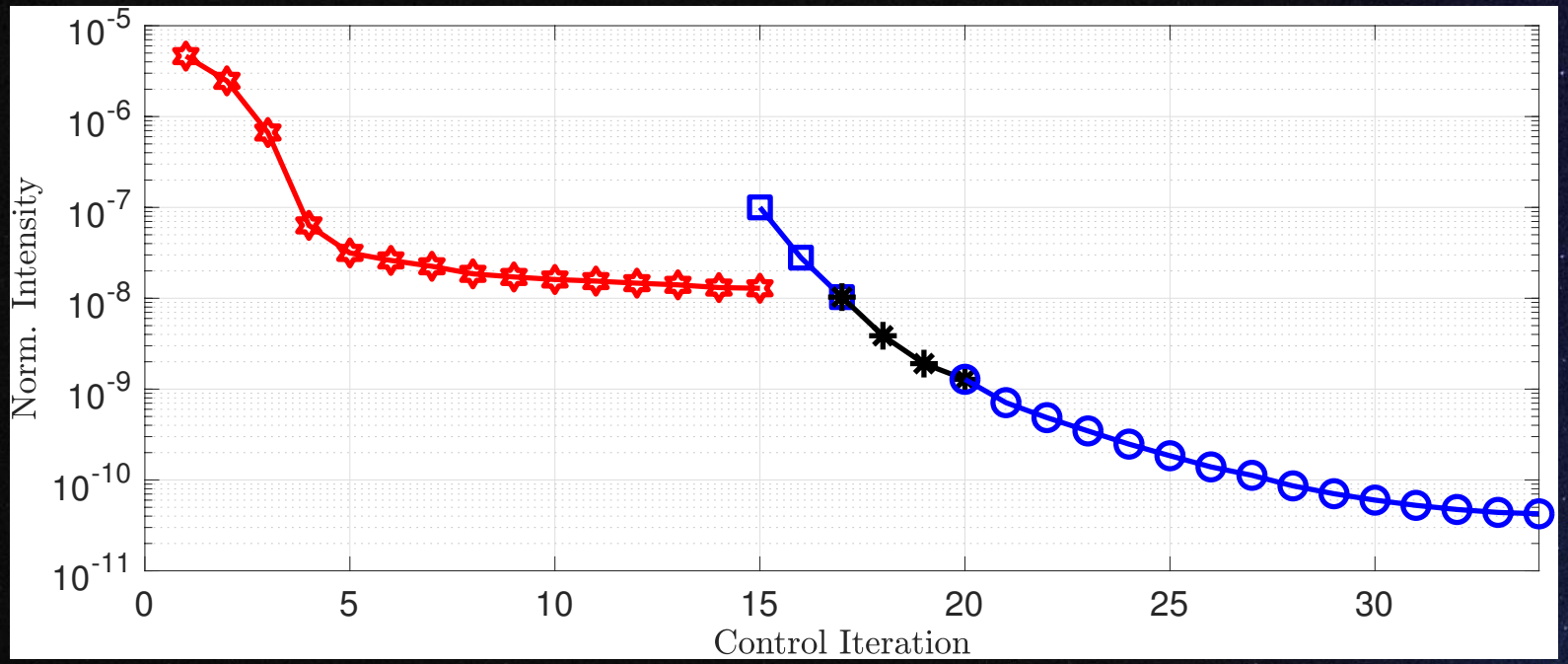
Results from a Design Run 1

FPM Amplitude



FPM Phase





Optimization Variables in Each Step:

DMs only

DMs + FPM amp

DMs + FPM phase

DMs + FPM phase + FPM amplitude

Robustness to L.O. Zernikes

Zernike Representations in 1-D

Radial polynomials [edit]

The first few radial polynomials are:

$$R_0^0(\rho) = 1$$
$$R_1^1(\rho) = \rho$$
$$R_2^0(\rho) = 2\rho^2 - 1$$
$$R_2^2(\rho) = \rho^2$$
$$R_3^1(\rho) = 3\rho^3 - 2\rho$$
$$R_3^3(\rho) = \rho^3$$
$$R_4^0(\rho) = 6\rho^4 - 6\rho^2 + 1$$
$$R_4^2(\rho) = 4\rho^4 - 3\rho^2$$

Wikipedia

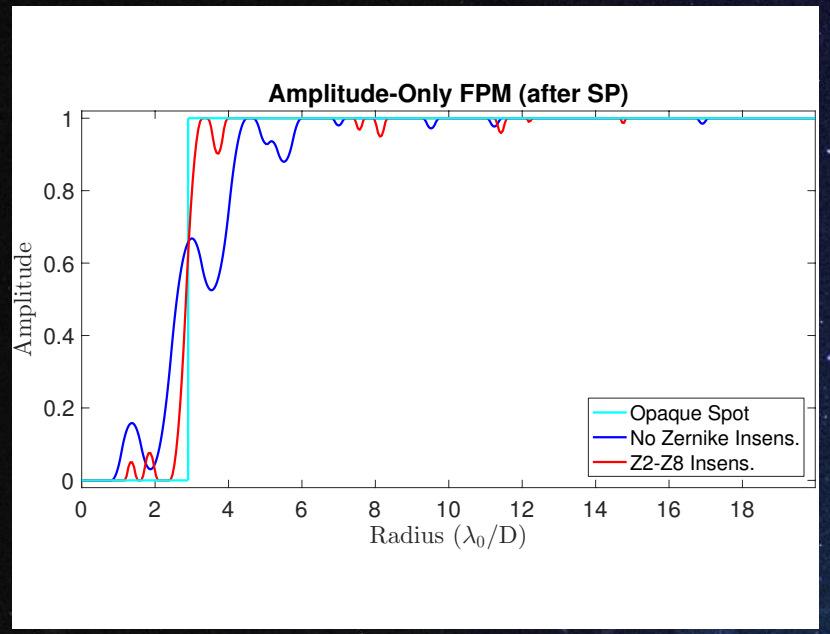
Target Values

(from VC6 performance)

Aberration	Indices			Allowable RMS wavefront error per mode (nm)			
	Noll	n	m	$l = 4$	$l = 6$	$l = 8$	$l = 10$
Tip-tilt	2,3	1	±1	1.1	5.9	14	26
Defocus	4	2	0	0.81	4.6	12	26
Astigmatism	5,6	2	±2	0.007	1.1	0.9	4.6
Coma	7,8	3	±1	0.006	0.66	0.82	5
Trefoil	9,10	3	±3	0.007	0.006	0.57	0.67
Spherical	11	4	0	0.005	0.51	0.73	6.3

Table from G. Ruane, "Vortex coronagraphs for the HabEx Mission Concept", JATIS, 2018.

Related Example (but for Shaped Pupil Lyot Coronagraph)



Summary and Future Work

1. Finish adding L.O. Zernike robustness into optimization

2. Include thin film properties in FPM
   1. (amplitude, phase) → (metal, dielectric)

3. Compute scientific yields
   - AYO (C. Stark),
   - EXOSIMS (D. Savransky)

4. Fine tune input parameters to maximize science yield