Segmented Coronagraph Design and Analysis (SCDA)

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With inputs from Garreth Ruane (CIT), Jeff Jewell (JPL), John Codona (UA), Neil Zimmerman (STScI), Chris Stark (STScI)

Task Objectives

Assuming stars with realistic finite angular size, which coronagraph designs enable telescopes with large segmented and obscured apertures to directly image exo-earths in the habitable zones around the nearest stars?

What changes to the reference apertures (primary and secondary mirrors) would enable coronagraph designs to meet the exo-earth contrast and IWA needs?

- Initial design investigation
- Collaboration/ Cross-fertilization encouraged
- Will inform technology gap and future technology investments.

What we're Funding

- APLC/SP: Soummer et al
- Vortex and HLC: Mawet, Ruane, Jewell
- PIAA: Guyon et al, including Belikov for CMC optimization and cross-fertilization
- Science yield tool (Princeton, working with ExEP tool and Stark tool)

Reference Apertures and Secondary Supports

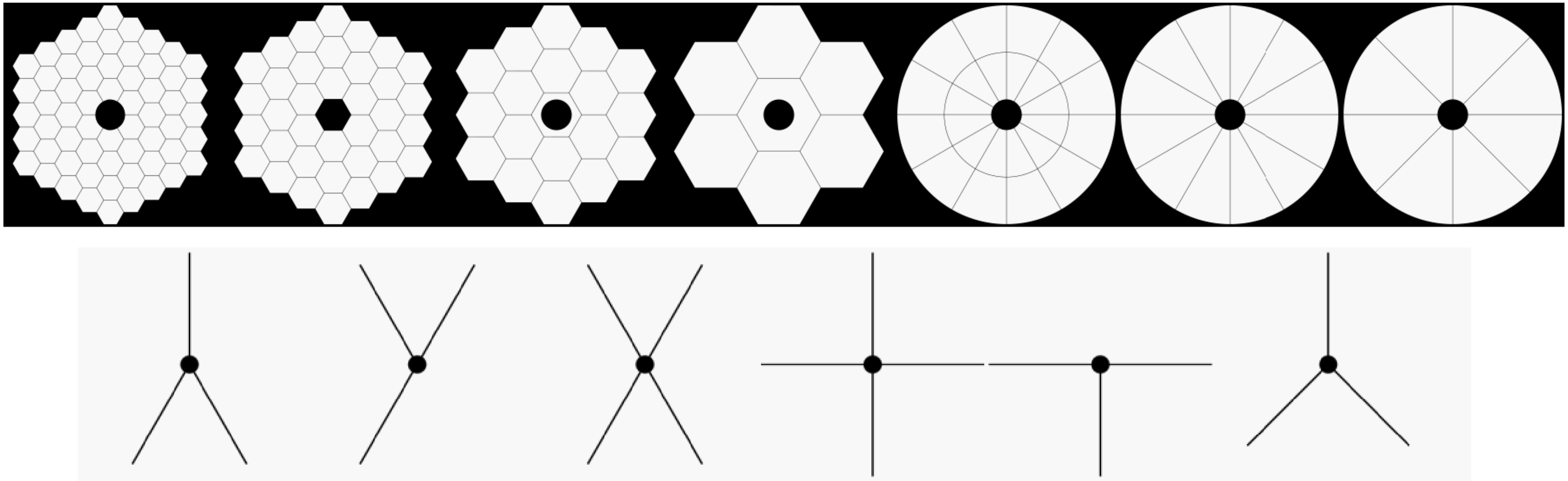


Figure 1 Apertures and secondary support structures selected for the study include four composed of hexagonal segments, one with keystone segments, and 2 with pie wedges. All are 12 m flat-to-flat or 12 m in diameter with 1.68 m diameter secondary obscurations (except the missing hex segment in the 3-ring hex). All segment edge gaps including edge roll-off are 20 mm wide. Secondary support strut widths are 25 mm and 100 mm. Aperture names, from left to right, are: 4-ring Hex, 3-ring Hex, 2-ring Hex, 1-ring Hex, Keystone-24, Pie wedge-12, and Pie wedge-8. Secondary supports are referred to as “Y”, “y,” “X”, and “T,” with two versions of “X” and “Y” for the respective hex and circular apertures.

Relative Design Merits

Table 1 Relative challenges of designs under consideration. Green to red designates least to most challenging. No absolute scale of difficulty is implied.

	APERTURES						
	4 ring	3 ring	2 ring	1 ring	Keystone 24	Pie wedge 12	Pie wedge 8
Segment Shape	Hex	Hex	Hex	Hex	Keystone	Pie wedge	Pie wedge
Max Segm. Dimension	1.54 m	1.98 m	2.77 m	4.62 m	2.5 m x 3.14 m	5 m x 3.14 m	5 m x 4.71 m
Segments							
Backplane							
Stability							
Launch Configuration							
SM Support							
Overall Ranking							

A document detailing the trades is available at:
http://exep.jpl.nasa.gov/files/exep/SCDAApertureDocument0504161.pdf

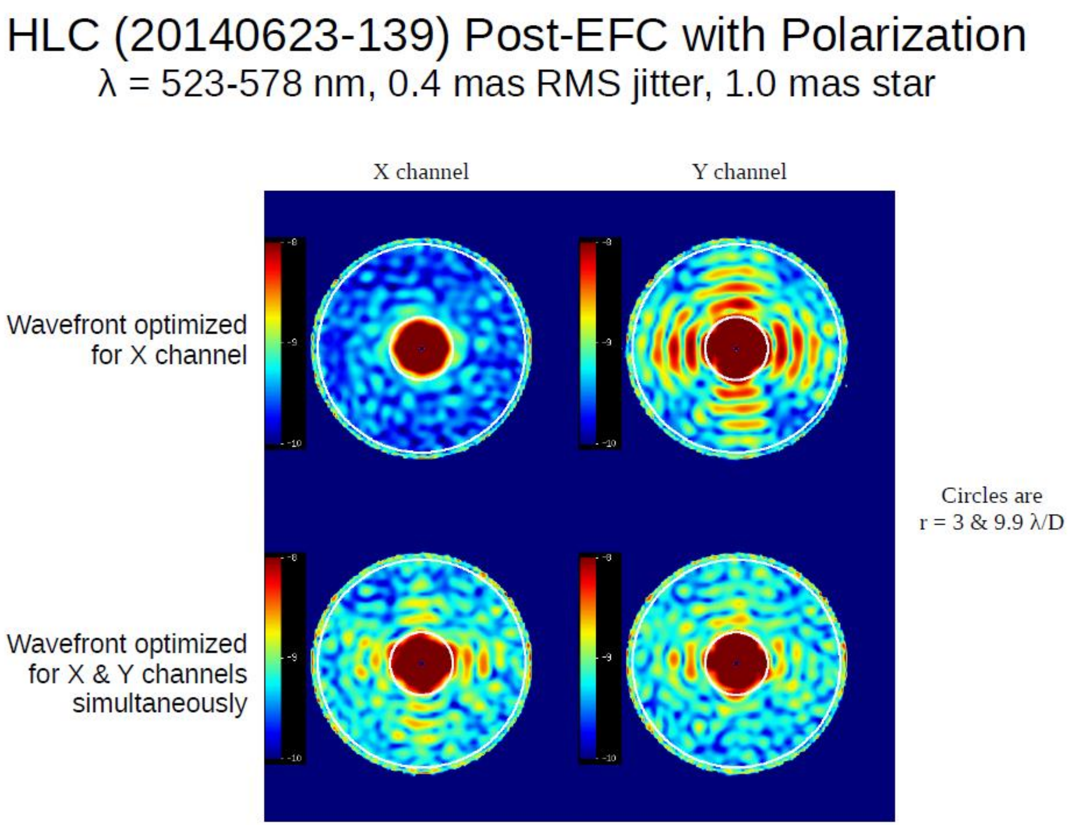
Authors: Feinberg, Hull, Knight, Lightsey, Matthews, Stahl, Shaklan

Telescope Parameters

- 12 m diameter
- f/1.25 primary
- 13.1 m to secondary
- 1.68 m secondary obscuration
- f/9.8 diffraction-limited Cassegrain focus on axis, few arcsec FOV
- TMA wide field design

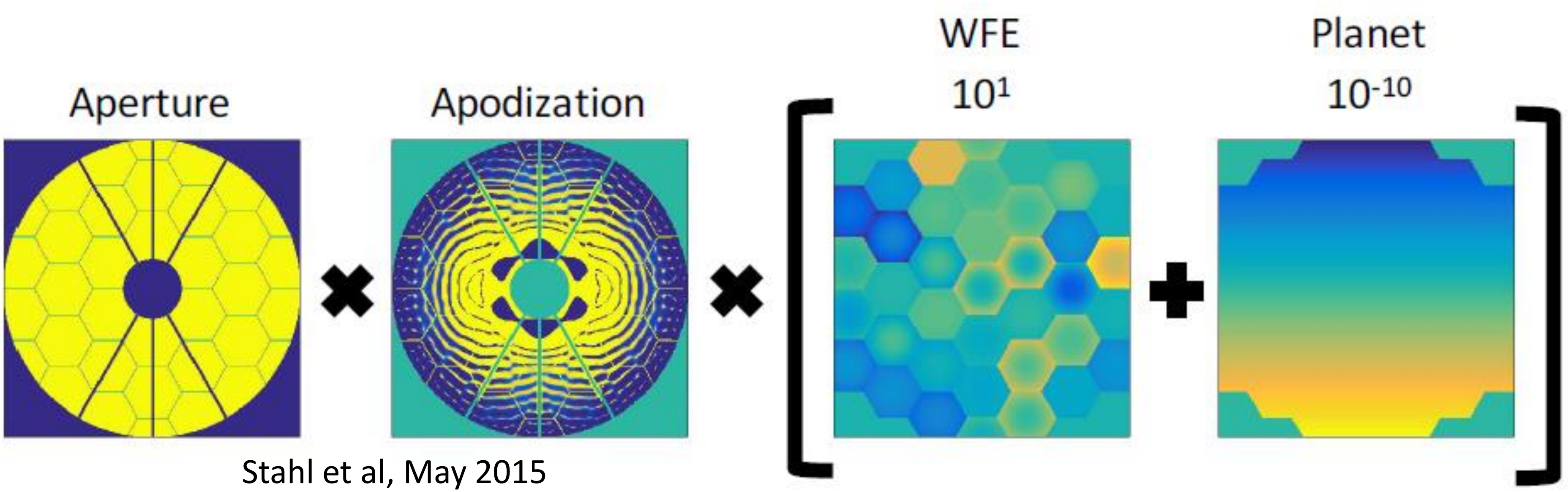
Polarization

- Ignore polarization for now.
- At f/1.25, we will need separate channels to correct each polarization.
- At f/1.25, cross-polarization in each channel will be acceptable (maybe 1e-10? 1e-9, TBD).



Pointing and Dynamics

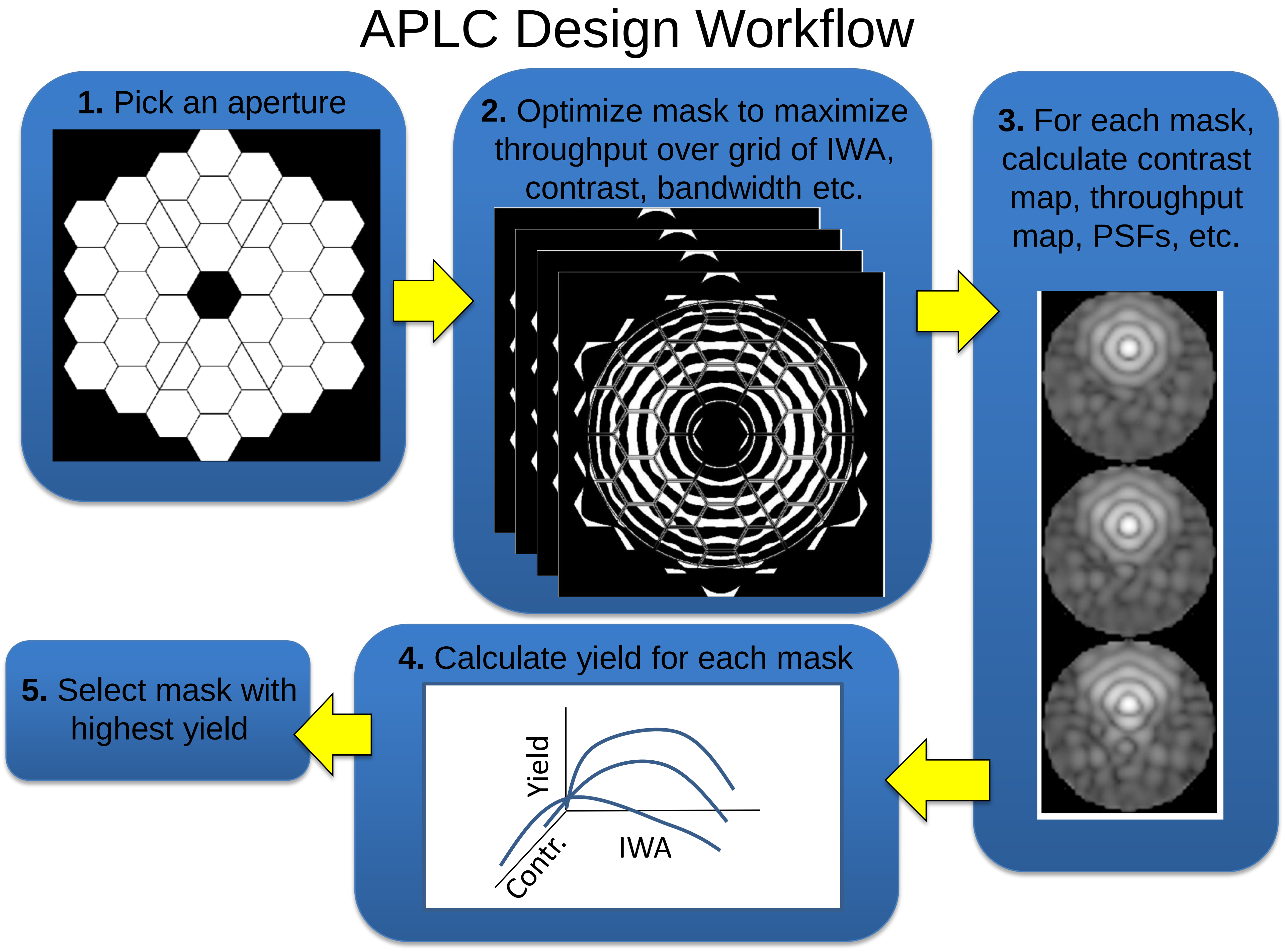
- Pointing
  - Assume pointing error is smaller than star diameter, e.g. ~1 mas.
  - Look at the fundamental performance limitation due to finite star diameter.
  - Later look at degradation at different pointing performance to set requirements.
- Segment motion
  - Ignore segment motion for now. All designs will have more or less the same sensitivity at a few lambda/D.



Stahl et al, May 2015

Optimize Science Return

- The goal is to optimize the science return of the designs, with focus on detecting HZ Earths.
  - Assume center of the band is 600 nm.
- Trade bandpass, IWA, OWA, throughput, contrast.


APLC Design Workflow
1. Pick an aperture
2. Optimize mask to maximize throughput over grid of IWA, contrast, bandwidth etc.
3. For each mask, calculate contrast map, throughput map, PSFs, etc.
4. Calculate yield for each mask
Yield
Contr.
IWA
5. Select mask with highest yield

Schedule

- Goal of a first ‘complete’ design by June 30.
  - No missing pieces, i.e., buildable stuff, no miracles
  - Science yield
    - APLC has workable solutions.
    - Vortex: consider how to build grey-scale mask.
    - Hybrid Lyot: needs broadband design
    - PIAA: No design update
- Final report January 2017
  - Science yield evaluated by ExEP
  - Performance verified by John Krist
- Possible follow-on funding.

STScI

This and following slides from Neil Zimmerman, STScI

SCDA survey strategy

1. Build on existing optimization code (linear programs in AMPL+Gurobi)

2. Automate the creation, execution, and harvesting of optimizations.

3. Test many parameter combinations by running on NASA's *NCCS Discover* supercomputer

4. Surveying dependence of throughput and PSF shape on telescope aperture geometry, inner working angle, FPM mask size, Lyot stop dimensions, bandwidth

Hexagonal APLC design survey, April 2016

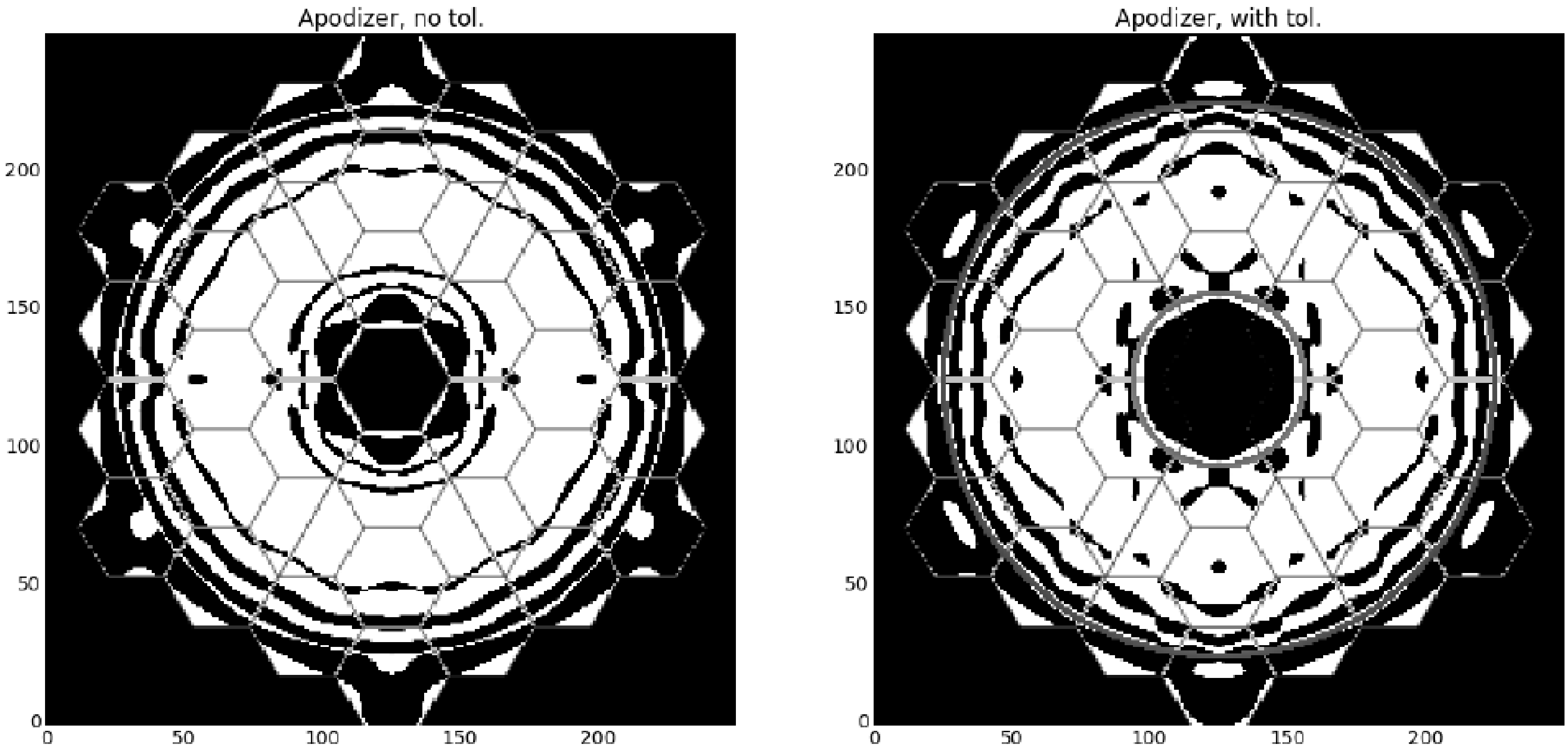
- 504 designs in total

- Fixed parameters: quarter-plane pupil symmetry, thin 'X'-shaped secondary struts, 1E-10 contrast, outer working angle 10 λ/D

- Varied parameters:

1. Aperture segmentation: hex1, hex2, hex3, hex4
2. Focal plane mask (inner dark zone) radius:
   3, 4, 5 λ/D (2.5, 3.5, 4.5 λ/D)
3. LS inner diameter: 20, 25, 30% of pupil diameter
4. LS outer diameter: 70, 72, 74, 76, 78, 80, 82%
5. Bandwidth:10% and 15% (3 and 5 wavelengths)

Example design for Hex3 aperture
4 - 10 λ/D, 15% BW



Hexagonal APLC survey results, 10% bandwidth

Provisional performance metric: "normalized throughput"

$$= \frac{\textbf{FWHM PSF throughput w.r.t. Telescope}}{\textbf{FWHM PSF area w.r.t. Telescope}}$$

Aperture segmentation

FPM radius		hex1	hex2	hex3	hex4
	3 λ/D	8.9%	12.1%	11.4%	11.1%
	4 λ/D	29.4%	32.4%	33.6%	32.7%
	5 λ/D	35.0%	35.0%	34.0%	34.1%

Hexagonal APLC survey results, 15% bandwidth

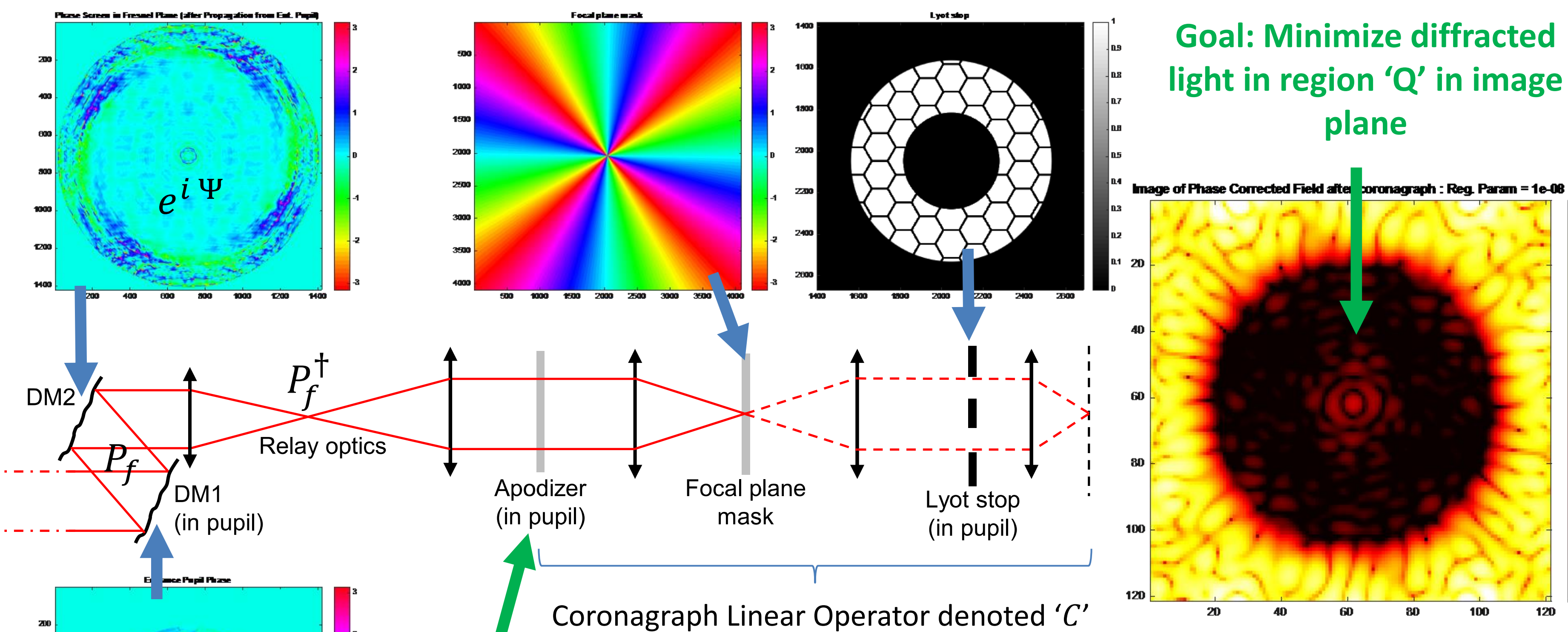
Provisional performance metric: “normalized throughput”

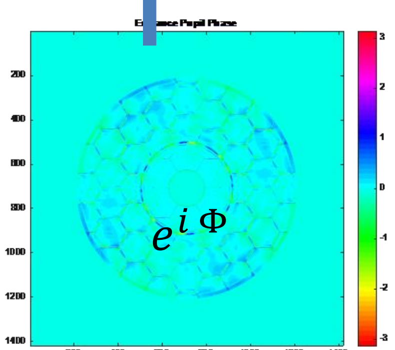
$$= \frac{\textbf{FWHM PSF throughput w.r.t. Telescope}}{\textbf{FWHM PSF area w.r.t. Telescope}}$$

Aperture segmentation

FPM radius		hex1	hex2	hex3	hex4
	3 λ/D	1.1%	1.1%	0.7%	1.1%
	4 λ/D	18.7%	31.1%	31.1%	30.0%
	5 λ/D	25.8%	33.5%	33.4%	32.4%

Iterative Solution of Phase Control with an Auxiliary Field (Jeff Jewell, JPL)





Aux Field, denoted 'W', lives in this plane!

Iteration to solve for phase control D.o.F:

1) $\min\limits_{W} \left(\|QCW\|^2 + \lambda \left\| W - P_f^\dagger e^{i\Psi} P_f e^{i\Phi} A \right\|^2 \right)$

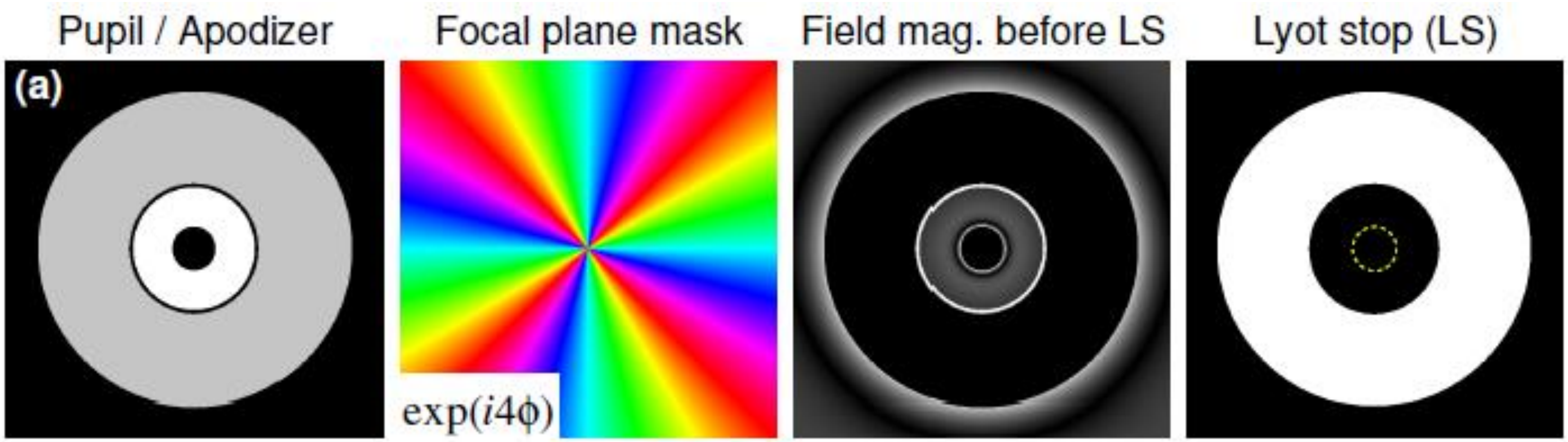
$$W = \left(\lambda I + C^\dagger Q C\right)^{-1} \lambda P_f^\dagger e^{i\Psi} P_f e^{i\Phi} A$$

2) $\min\limits_{\{\Psi,\Phi\}} \left\| W - P_f^\dagger e^{i\Psi} P_f e^{i\Phi} A \right\|^2$

- Fresnel Propagators denoted P_f and (backwards) $P_f^\dagger$
- Goal is to find phase solutions in the entrance pupil $e^{i\Phi}$ and out of plane $e^{i\Psi}$ for any aperture in order to directly minimize on-axis source light in the image plane "dark hole"

Advanced coronagraph designs for segmented aperture telescopes: apodized vortex and band-limited coronagraphs

Garreth Ruane[a], Jeffrey Jewell[b], Dimitri Mawet[a,b], Laurent Pueyo[c], and Stuart Shaklan[b]



Vortex solutions based on Ring Apodizer approach, solved using Auxiliary Field code.

Vortex Solution With Amplitude-Only Apodizer

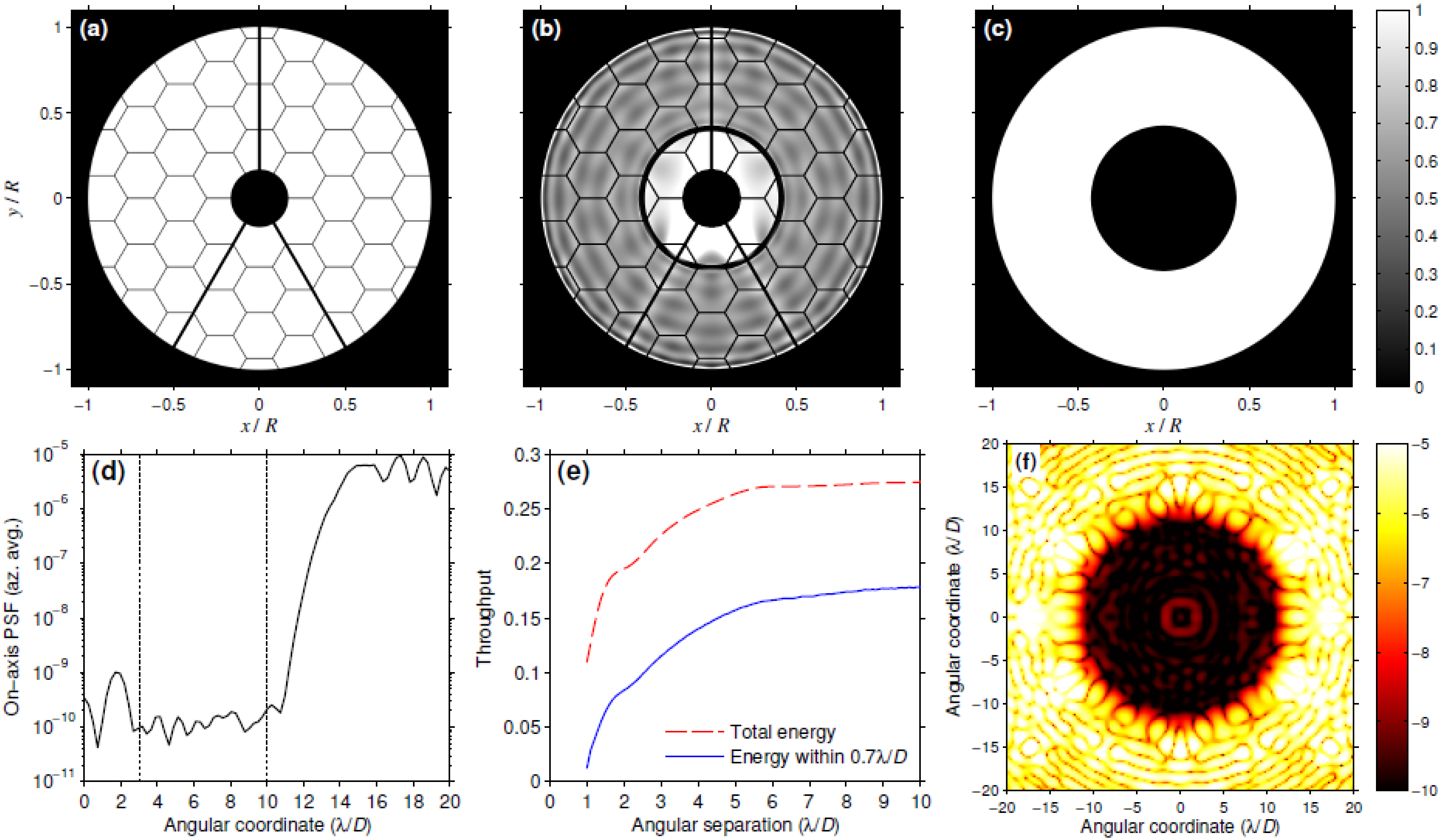


Figure 6. Apodizer for segmented aperture with four-rings of hexagonal mirrors and thick spiders.

Solution without Spiders

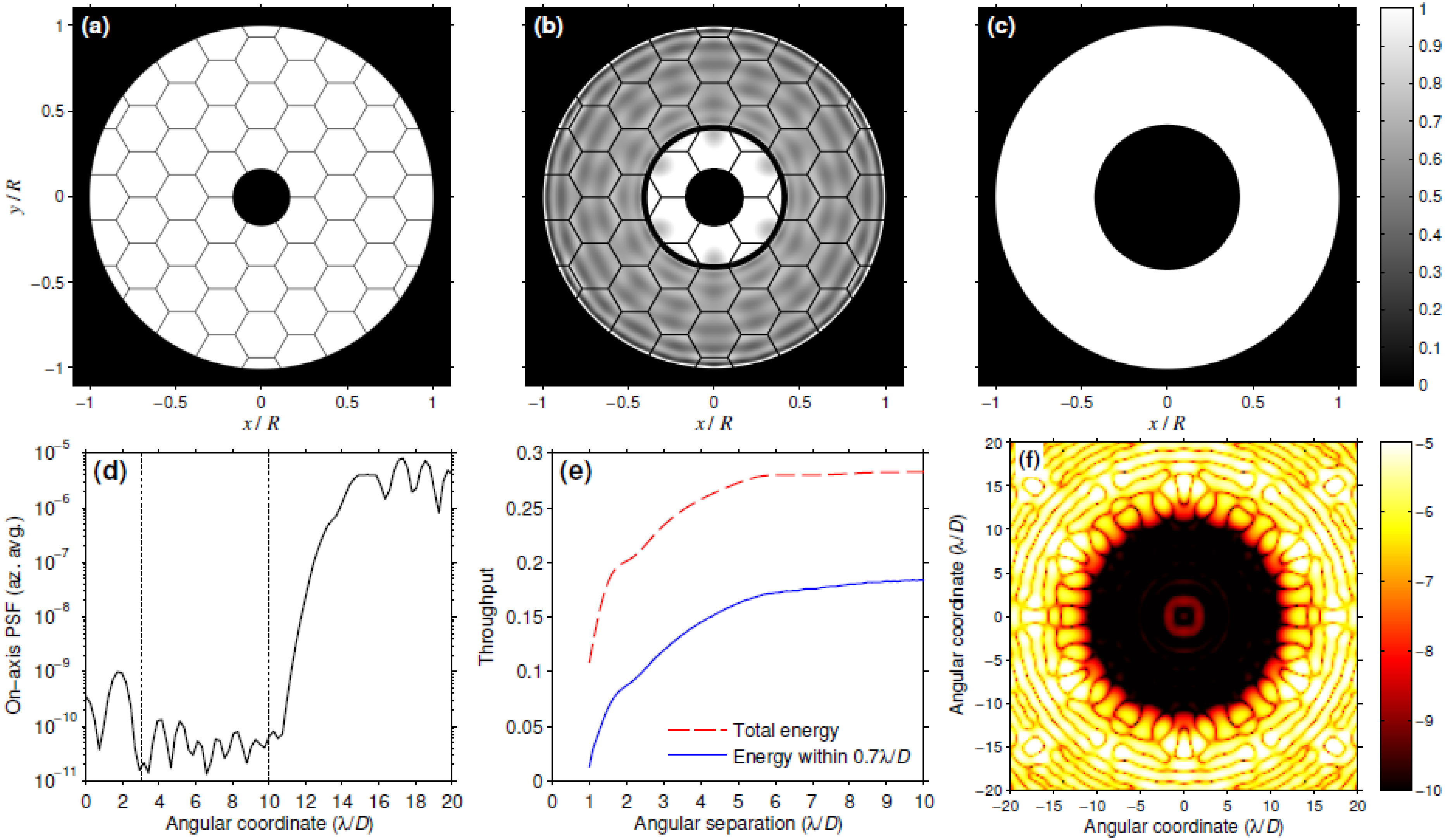


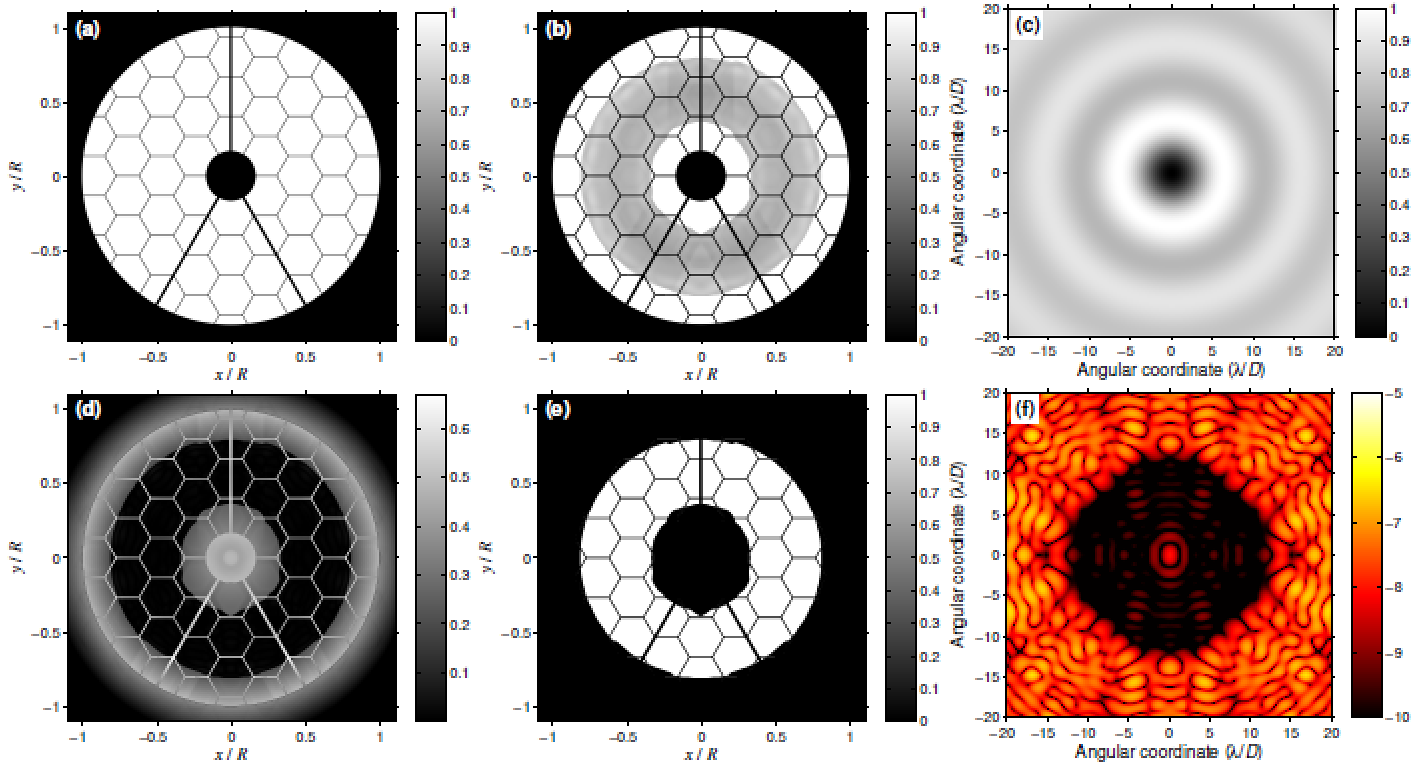
Figure 7. Apodizer for segmented aperture with four-rings of hexagonal mirrors and no spiders.

With a complex apodizer (e.g. generated using DMs), throughput will go up but image quality will go down.

Hybrid Lyot Model

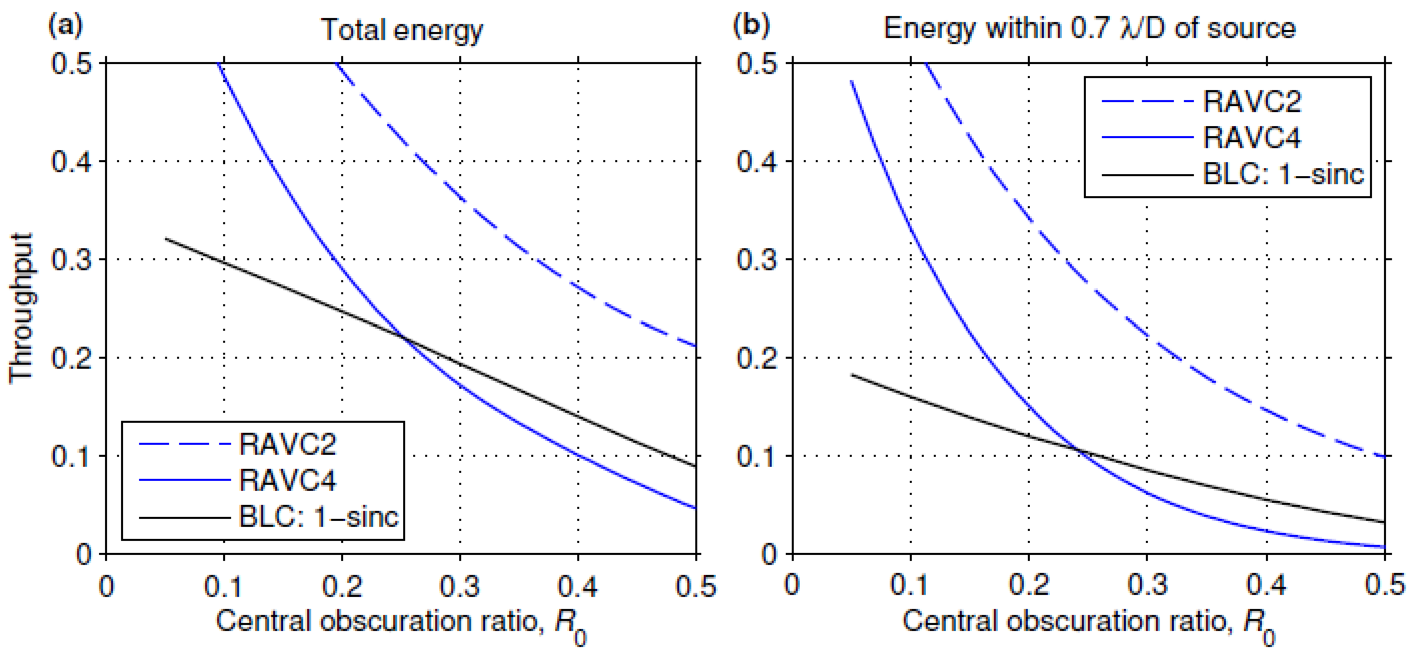
- Apodizers based on monochromatic aux. field solution.
- 1-sinc focal plane mask.
- Lyot stop found by thresholding the Lyot plane irradiance.
- Lyot stop and focal plane mask are jointly optimized for maximum throughput at $3 - 5\lambda/D$.
- Irradiance values are normalized to peak irradiance without coronagraph masks.

Clipped Hex4 pupil, band-limited coronagraph



Narrow band simulation ($\Delta\lambda/\lambda = 0.01\%$). (a) Entrance pupil. (b) Apodizer. (c) Focal plane mask. (d) Lyot plane field. (e) Lyot stop. (f) Stellar PSF.

Throughput vs. Secondary Mirror Size



X-axis is the ratio of secondary mirror diameter to primary mirro r diameter.
Note that these results are for amplitude-only mask and monochromatic solution.

PIAA Status at Guyon's Workshop, May 2016

3 main outstanding issues for PIAACMC:

- Understanding limits imposed by stellar angular size
- Managing light diffracted by gaps in realistic optical system (not Fraunhofer propagation)
- Understanding focal plane mask manufacturing limits… and propagation effects with small feature sizes

Mapping PIAACMC performance to science:

Small IWA, but sensitive to stellar angular size

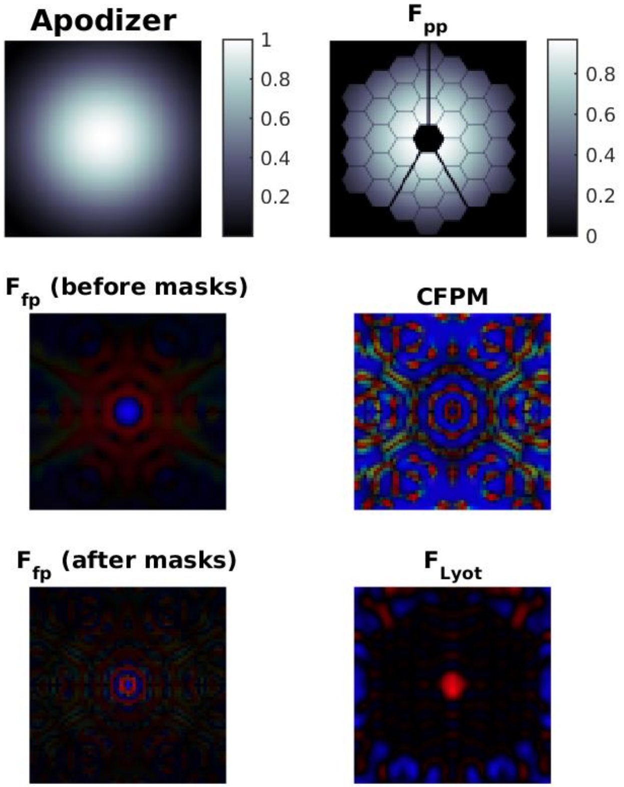
→ best suited for near-IR work, distant targets or cooler stars

(using PIAACMC to work at ~5 l/D is probably not an optimal solution)

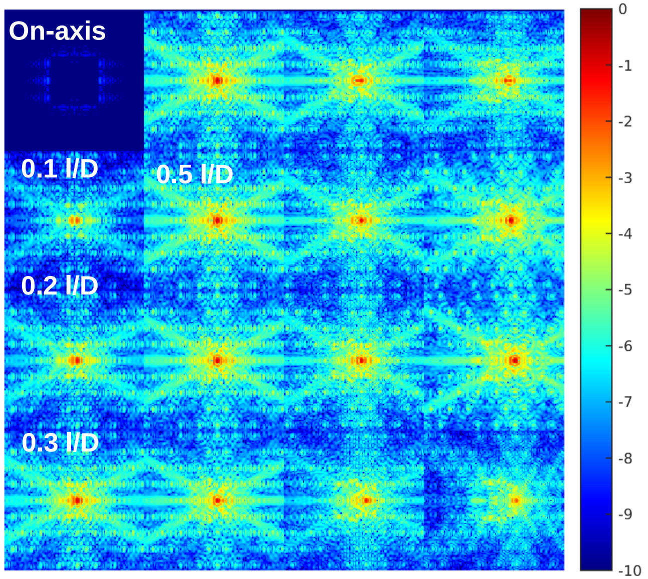
Linear Lyot Coronagraph Theory

Dr. Johanan L. Codona, University of Arizona

Concept: Express the electric field in various planes within a coronagraph as a vector of samples on a grid. Write this as a vector in complex Hilbert space. An arbitrary APCMLC coronagraph can be written as a series of linear matrix operations. By considering specific incident fields (say, light from an on-axis unresolved star), we can combine the coronagraph operators to relate downstream fields to coronagraph components such as the apodized pupil (AP) or the complex focal plane mask (CFPM). Each of the resulting operators can be analyzed in terms of its natural "modes" and used to find the apodization or the CFPM as eigenvectors or by projecting out undesired modes. Enhancing the coronagraph to work with resolved stars and non-monochromatic light is achieved by applying related linear operators and projections to the CFPM.



The result is a robust and intuitive mathematical and numerical framework for designing high-performance Lyot coronagraphs with an apodized pupil and a complex focal plane mask.



Manufacturable Complex Focal Place Masks Using Phasor Dithering

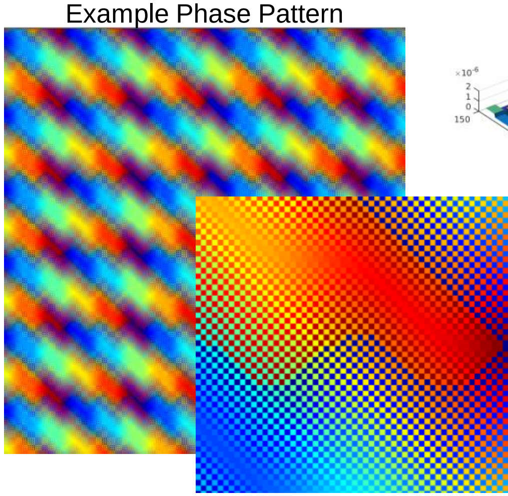
Dr. Johanan L. Codona, University of Arizona

Designs based on the linear Lyot coronagraph theory result in pupil transmission apodization patterns and complex (transmission and phase) focal plane masks. The apodization can be implemented using conventional transmission masks or PIAA optics.

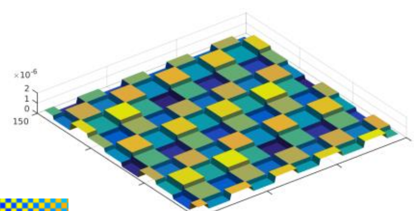
A complex focal plane mask requires a varying transmission and phase be applied at different positions. This is further complicated when the theory is used to determine how the complex mask must vary with wavelength.

Fortunately, since the coronagraph will always contain a “Lyot Stop” in a downstream pupil plane, the effect of a focal plane mask is smoothed, allowing us to build a complex mask out of small phase-only pixels. In a reflecting implementation, the phase pixels are simply small etched pits with different depths. Depending on the wavelength, neighboring phase pixels *phasors* ($e^{i\phi}$) can constructively or destructively interfere, resulting in both transmission and phase in the smoothed reflectance. Adding extra multiples of 2π phase in different pixels, the desired wavelength dependence can be approximated.

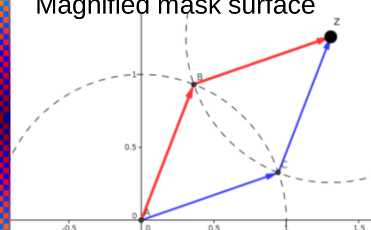
Example Phase Pattern



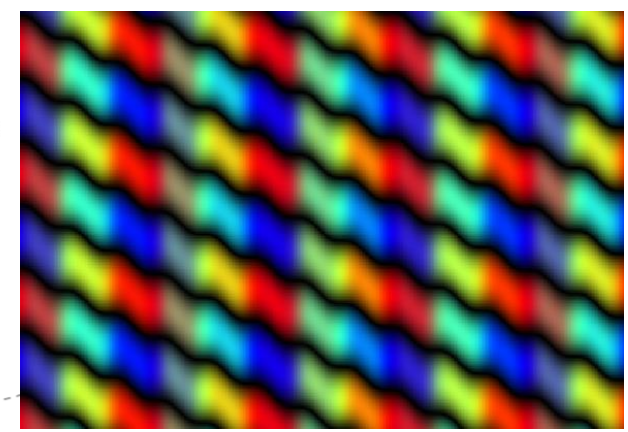
Magnified phase pattern



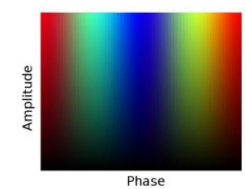
Magnified mask surface



2-phasor sum in complex plane can give general complex value



Smoothed phasor pattern



Summary

- Exciting (and fun!) work going on in segmented coronagraph design.
- Finding novel and surprising solutions.
- BUT, don't mistake designs for ease of implementation.
  - High contrast on a any aperture, especially a segmented aperture, is extremely challenging!
- The next phase of the effort, in FY17, will be to look at tolerances, especially to telescope pointing and segment motions.