Evaluating Coronagraph Performance with End-to-End Numerical Modeling: WFIRST and Beyond

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Stages of Coronagraph Design

Concept
Mathematical, perfect modulations of the wavefront, perhaps only monochromatic

Realize
How to modify wavefront with real materials and devices?

Build
Fabricate & measure components

Testbed
Test system on ground

Fly
Use system for science
Coronagraph Optimization: The Past

- Contrast
- Inner working angle
- Transmission
Coronagraph Optimization: Now

- Contrast
  - aberrations, jitter, finite star diameter, bandwidth, DM stroke
- Inner working angle
  - jitter, finite star diameter, aberrations, bandwidth
- Effective Throughput
  - planet PSF morphology, mask transmission
- Wavefront control
  - ACAD, DM control spatial frequencies, stroke limits, polarization, bandwidth
End-to-End Modeling

- Propagation through all significant optical components, with realistic defects
  - PROPER* used for WFIRST & Exo-C modeling
- Wavefront control using deformable mirrors and wavefront optimization algorithms (EFC, stroke minimization)
- Jitter, finite stellar diameter
- Potential misalignments (pupil)
- Evaluation of field (planet) PSFs

*Available from proper-library.sourceforge.net
WFIRST Coronagraph Downselect

- Coronagraph advocates submitted their designs in 2013
  - Hybrid Lyot (HLC)
  - Shaped Pupil (SPC)
  - PIAACMC
  - Shaped pupil + ACAD + vortex
  - Visible nuller (two types; modeling incomplete)
- Evaluated via end-to-end modeling
  - Dig a dark hole around the star in a realistically aberrated system with DMs and EFC wavefront control
  - Determine contrast degradation due to pointing jitter
  - Determine field (planet) PSF properties
- Used model-derived properties to predict planet yields for different jitter levels and post-processing factors
- Downselected to HLC, SPC, & PIAACMC (backup)
  - revised designs with improved efficiencies and jitter tolerances have been provided
- A similar process was done for the Exo-C Probe study (unobscured telescope with HLC, classical PIAA, vector vortex)
- WFIRST modeling described in Krist et al., JATIS, v.2, 011003 (2016)
Optical Surface Error Maps

Measurement-based Synthetic Primary

Measurement-based Synthetic Secondary

Measured GPI Optic

Synthetic CGI Optic

OAP

Flat
Dark Hole Generation Process

1. Initial state
   - Initial state: ~10^-4 contrast

2. "Flatten" the wavefront (phase retrieval)
   - "Flatten" the wavefront: ~10^-6 contrast

3. Sense image plane E-field\(_{\lambda}\) (DM probing)

4. Determine DM settings (EFC)

5. Evaluate new DM solution
   - EFC Iter 1: 4 x 10^-8
   - EFC Iter 2
   - EFC Iter 3
   - EFC Iter 4
   - EFC Iter 5
   - EFC Iter 6

6. Converged?
   - No
   - Yes
   - ~10^-9 contrast

Before any WFC (10^-4) Flattened (10^-6) EFC Iter 1 (4 x 10^-8) EFC Iter 2

EFC Iter 3 EFC Iter 4 EFC Iter 5 EFC Iter 6
PIAA Schematic

PIAA M1 apodizes beam via compression

PIAA M2 corrects phase errors caused by beam compression

Focal plane mask

Beam @ M1

Beam @ M2
PIAA with Wavefront Control

With measured M2 Errors, Post-EFC
No M2 Errors Post-EFC

From Internal Coronagraph Modeling Milestone #2 Results Report by Krist et al.: exep.jpl.nasa.gov/technology
WFIRST Coronagraph Aberration Sensitivities

100 picometers RMS of aberration

**HLC**

**SPC**

**PIAACMC**
WFIRST Dark Holes with Pointing Jitter & Finite Star

WFIRST PIAACMC uses a single DM for simplicity, so it has a single-sided dark hole.
WFIRST Polarization: $WFE_Y - WFE_X$

<table>
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<tr>
<th>Wavelength (nm)</th>
<th>RMS WFE</th>
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<tbody>
<tr>
<td>450</td>
<td>0.013 waves</td>
</tr>
<tr>
<td>550</td>
<td>0.003 waves</td>
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<tr>
<td>650</td>
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<td>850</td>
<td>0.006 waves</td>
</tr>
<tr>
<td>950</td>
<td>0.007 waves</td>
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</table>

See tomorrow’s talk by Shaklan
HLC Post-EFC with Polarization (523-578 nm)

Optimized for X polarization only

Optimized for both polarizations simultaneously

Circles are $r = 3 & 9.9 \lambda/D$

*Polarization-induced aberration is mainly astigmatism due to the f/1.2 primary.*
Time-Dependent Speckle Variations
Wavefront changes from thermal & structural modeling
Hybrid Lyot Coronagraph Planet PSF

\( \lambda = 509 - 591 \text{ nm}, r = 3 - 9 \lambda/D, \)

7x10^{-10} IWA contrast (10^{-4} without DM patterns)

Lyot stop (grey)

Obscuration-compensating DM patterns (200 nm P-V stroke)

Planet PSFs

DMs off

DMs on
Hybrid Lyot Coronagraph: Exo-C & WFIRST

![Graph showing Planet PSF Encircled Energy vs. λ/D](image)

- Exo-C
- WFIRST (DMs off)
- WFIRST (DMs on)
WFIRST Coronagraph Field PSF EE

WFIRST        34.0%
HLC            4.5%
SPC            3.7%
PIAACMC        14.0%

Encircled energy

\( \frac{\lambda}{D} \)

WFIRST
PIAACMC
SPC
HLC

PSF Core Throughput

WFIRST 34.0%
HLC 4.5%
SPC 3.7%
PIAACMC 14.0%
WFIRST RV Planet Yield Estimates

From Traub et al., JATIS, v.2, 011020 (2016)

See talks by Stark, Morgan in this workshop.
Segmented Telescope Coronagraph Considerations

**Effective throughput**
- *Planet PSF morphology*

**Aberration sensitivity**
- *Segment-to-segment piston, global low-order, wavefront jitter*

**Jitter & finite stellar diameter**

**DM patterns (ACAD)**
- *Affect on PSF morphology, increased aberration & jitter sensitivities, stroke limitations*

**Alignment tolerances**
- *Mask-to-pupil registration, pupil distortion*
Stages of Coronagraph Design

- **Concept**
  - Model with a realistic telescope
  - Does it work?
    - NO
    - YES

- **Realize**
  - Model with a realistic telescope
  - Does it work?
    - NO
    - YES

- **Build**
  - Model with a realistic telescope
  - Does it work?
    - NO
    - YES

- **Concept or Realize or Build**
  - Does it work?
    - NO
    - YES

- **Testbed**
  - Does it work?
    - NO
    - YES

- **Fly**