WFIRST/AFTA Coronagraph Technology Development: Recent Results and Plan to TRL5


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Outline

- WFIRST / AFTA Coronagraph Overview
- Shaped Pupil Coronagraph Status
- Hybrid Lyot Coronagraph Status
- Low Wavefront Sensing and Control
- Flight Instrument Design
- Integrated Modeling
- Summary
Coronagraph Technology Development

- WFIRST/AFTA baseline includes 1st high-contrast coronagraph in space
  - Must work with the obscured pupil 2.4 meter AFTA telescope and observatory “as is”

- Coronagraph is a tech demo, but produces precursor science
  - Exoplanet direct imaging and spectroscopy
  - Orders of magnitude improvement over existing instruments
Coronagraph Technology Development

- Technology Development Plan for maturing coronagraph technology to TRL 5 by 9/30/2016 was developed and approved
  - Working toward testbed demonstration of starlight suppression that meets science requirements in presence of optical wavefront disturbances expected on orbit
  - Mature key components – spectrograph detector and deformable mirror – to TRL6
  - 9 key milestones
  - Passed 2 of them, plan execution currently ahead of schedule

- Progress monitored by independent Technology Assessment Committee (TAC)

- Many institutions involved in coronagraph technology development and science
Selected Architecture: Occulting Mask Coronagraph

- Primary architecture: Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot
- SP and HL share same optical layout
- Operate with different apodizing and occulting masks
- In “HL mode,” OMC affords potential for greater science, taking advantage of good thermal stability in GEO and low telescope jitter for most of the reaction wheel speeds
- In “SP mode,” OMC provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost / schedule risk.

![Diagram of Shaped Pupil, Post-EFC contrast graph](image)
Milestone 1: Reflective Shaped Pupil Mask

- SPC masks designed at Princeton and manufactured at JPL
- Reflective aluminum on highly absorptive black silicon
- Characterized effects of mask imperfections on coronagraph contrast
- Milestone 1 results submitted on 6/16/2014, approved by TAC

<table>
<thead>
<tr>
<th>Imperfection Type</th>
<th>Measured Level</th>
<th>Delta contrast after WFC</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Si refl., specular</td>
<td>&lt;7x10^-8</td>
<td>&lt;2.1x10^-10</td>
<td>Upper bound; limited by measurement setup</td>
</tr>
<tr>
<td>Black Si refl., diffuse</td>
<td>&lt;0.6%</td>
<td>&lt;10^-11</td>
<td></td>
</tr>
<tr>
<td>Mask WFE</td>
<td>~0.036(\lambda) rms (above focus)</td>
<td>7x10^-11</td>
<td>Post WF control - Better wafers received</td>
</tr>
<tr>
<td>Isolated defects</td>
<td>Small pinholes and 2 scratches</td>
<td>8x10^-12</td>
<td>Post WF control</td>
</tr>
<tr>
<td>Al refl. variations</td>
<td>~0.5%</td>
<td>fully correctable</td>
<td>Post WF control</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>&lt;3x10^-10</td>
<td>Upper bound</td>
</tr>
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Milestone 2: SPC Testbed Demonstration

- Obtained narrowband (2%) and early broadband (10%) starlight suppression results in the shaped pupil coronagraph testbed
  - Initially with 1 DM, stopped down to 48x48 actuators
  - Milestone 2 results submitted on 9/17/14, approved by TAC
  - Broadband result meets Milestone 5 success criterion 12 months early
- Retired the biggest technology development risk, proving that high contrast is achievable with the obscured AFTA telescope pupil
- Starting fabrication of Gen 2 SPC masks (with Lyot stop) designed at Princeton for improved IWA and throughput

![Contrast vs. radius graph](chart.png)

- 550 nm, 2% BW
  - Mean cont. $\sim 6 \times 10^{-9}$
- 550 nm, 10% BW
  - Mean cont. $\sim 9 \times 10^{-9}$
Hybrid Lyot Mask and Testbed

- Circular HLC mask successfully fabricated and characterized
  - Modeling of mask imperfections predicts good contrast
- HLC testbed aligned and calibrated in a vacuum chamber – nulling experiments in progress
  - Working with two 48x48 DMs and new driving electronics
- Milestone 4 (HLC narrowband contrast) due 2/28/2015
Low Order Wavefront Sensing / Control

- LOWFS/C uses rejected starlight from the coronagraph
  - Picked up from focal plane occulter (HLC) or field stop (SPC)
  - Senses and corrects LoS jitter, senses Z4-Z11
- Selected Zernike wavefront sensor
  - Zernike phase dimple on HLC and SPC focal plane masks
  - First masks received and are being tested
- Baseline and characterized high TRL camera and fast steering mirror inherited from SIM
- OTA simulator with 2” AFTA prescription telescope
Coronagraph Flight Design

- As a tech demo, coronagraph cannot drive mission level requirements:
  - Telescope coatings, wavefront errors, obscurations
  - Observatory orbit, pointing jitter and drift, down-link
- Significant early effort to mature flight instrument design
- Our assessment is that the coronagraph will meet its performance requirements with the existing telescope and observatory constraints
Coronagraph Integrated Modeling

- Developed and analyzed a realistic operational scenario
  - Worst case thermal loading changes
- Integrated STOP modeling of telescope and coronagraph
- Early results are very promising for speckle stability in the dark hole and expected post-processing gain

A measure of the expected post-processing effectiveness is the speckle subtracted images between two stars
Initially, with spectra of both stars assumed flat, we find implied PP effectiveness (thermal only):

\[ f_{pp} = \frac{\sigma_{SSI}}{\langle S \rangle} \approx \frac{1}{25} \]
Summary

• WFIRST-AFTA Coronagraph team is executing Technology Development Plan to mature the coronagraph to TRL 5 by 9/30/2016

• Work currently proceeding ahead of schedule

• Progress highlights in 2014:
  – Both HLC and SPC delivered improved designs that increase science yield with obscured telescope pupil, realistic observatory jitter
  – Shaped pupil coronagraph: mask fabricated and characterized; demonstrated high contrast in testbed in 2% and 10% spectral bandpass
  – Hybrid Lyot coronagraph: circular masks fabricated and characterized, testbed nulling experiments in progress
  – LOWFS/C concept selected and is being implemented
  – Significant progress in flight instrument design and integrated modeling of the coronagraph
## WFIRST-AFTA Coronagraph Key Milestones

<table>
<thead>
<tr>
<th>MS #</th>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than $10^{-4}$ and 20 μm pixel size.</td>
<td>7/21/14</td>
</tr>
<tr>
<td>2</td>
<td>Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.</td>
<td>9/30/14</td>
</tr>
<tr>
<td>3</td>
<td>First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm.</td>
<td>12/15/14</td>
</tr>
<tr>
<td>4</td>
<td>Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.</td>
<td>2/28/15</td>
</tr>
<tr>
<td>5</td>
<td>Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment.</td>
<td>9/15/15</td>
</tr>
<tr>
<td>6</td>
<td>Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.</td>
<td>9/30/15</td>
</tr>
<tr>
<td>7</td>
<td>Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.</td>
<td>8/25/16</td>
</tr>
<tr>
<td>8</td>
<td>PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.</td>
<td>9/30/16</td>
</tr>
<tr>
<td>9</td>
<td>Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.</td>
<td>9/30/16</td>
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Top Level Technology Development Schedule
• **Coronagraph testbeds**
  – Over a decade of successful operation at JPL
  – World record levels of contrast with unobscured and (now) obscured pupil
  – 4 testbeds operational in vacuum
  – Fully equipped, experienced personnel

• **Coronagraph Mask Fabrication**
  – Shaped pupil and hybrid Lyot masks made at MicroDevices Lab at JPL
  – World class nano-fabrication facility
  – Experienced in fabrication of flight hardware
Dynamic Broadband Demo: Milestone 9 (9/30/16)

- **Milestone 9**: Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.
- Dynamic coronagraph testbed will be built and aligned by July 2015
- Interfaces with OTA simulator and contains LOWFS/C components
- Optical layout replicates flight OMC instrument
- Incorporates next generation of masks
- Designed with TRL5 model validation requirements in mind