AFTA Coronagraph
Preliminary Design

WFIRST SDT Meeting #1

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Stuart Shaklan

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Long History of Coronagraph Mission Studies

- **2004-07: Terrestrial Planet Finder Coronagraph (TPF-C) SDT**
  - Flagship: 8x3.5m off-axis
  - Primary Goal: Earth detection and characterization
  - Coronagraph: Lyot mask at 4 \( \lambda/D \) and 10\(^{-10} \) Contrast
  - Requirements and performance well understood.
  - Modeling capabilities for error budgets & performance

- **2008-09: Astrophysics Strategic Mission Concept Studies (ASMCS)**
  - Several probe-scale coronagraph studies (<$800M – $1B)
  - ACCESS (Lyot), PECO (PIAA), EPIC (Visible Nuller)
  - Approach: ~ 1.5m Telescopes, < 3 \( \lambda/D \) and 10\(^{-9} \) Contrast
  - Science Goals: Jupiters & some Super-Earths detection & characterization, Exo-Zodi, Planetary Systems

- **2011- on-going: Exoplanet SDT**
  - Flagship Mission Requirements (2012, Greene & Noecker)
  - Probe Mission Requirements (2013-14)
Study Approach

• Main objective: EXISTENCE PROOF
  – Demonstrate feasibility, science, performance and cost of a coronagraph instrument on WFIRST-AFTA

• Time & funding will permit only 1 design cycle
  – Future studies will consider more aggressive & riskier coronagraphs which optimize science & performance

• FOR NOW Use Lyot coronagraph layout: best understood, models validated and applicable to several coronagraph types:
  – Lyots, Shaped Pupil and Vector Vortex share same configuration
  – PIAA and Visible Nullers require unique optical configurations

• Coronagraph Instrument consists of 3 components:
  – Coronagraph for broadband starlight suppression
  – Low Order Wave Front Sensor (LOWFS) for tip/tilt pointing and later possibly low order aberration control
  – Integral Field Spectrometer for characterization
### Coronagraph Performance Goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandpass</td>
<td>400-1000 nm</td>
<td>Will likely require sequential measurement in 20% wide bands</td>
</tr>
<tr>
<td>Inner Working Angle</td>
<td>100 mas</td>
<td>at 400 nm, $3\lambda/D$ driven by challenging pupil</td>
</tr>
<tr>
<td></td>
<td>250 mas</td>
<td>at 1 um</td>
</tr>
<tr>
<td>Outer Working Angle</td>
<td>1 arcsec</td>
<td>at 400 nm, limited by 64x64 DM</td>
</tr>
<tr>
<td></td>
<td>2.5 arcsec</td>
<td>at 1 um</td>
</tr>
<tr>
<td>Contrast</td>
<td>1.E-09</td>
<td>Cold Jupiters, not exo-earths. Deeper contrast looks unlikely due to pupil shape and extreme stability requirements.</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>70</td>
<td>at 700 nm, Linearity TBD.</td>
</tr>
<tr>
<td>IFS Spatial Sampling</td>
<td>17 mas</td>
<td>This is Nyquist for $\lambda$ 400 nm.</td>
</tr>
</tbody>
</table>
## Coronagraph Instrument

<table>
<thead>
<tr>
<th>Coronagraph Type</th>
<th>Designed to support Lyot and shaped pupil coronagraphs. Lyot has best performance to date. Shaped pupil may be superior for the complex obstructions of this telescope.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>Room Temperature, due to DM wavefront specifications.</td>
</tr>
<tr>
<td>Deformable Mirrors</td>
<td>Two 64x64 devices, sequentially placed for broadband dark hole control. Current design is for MEMS DM with 300 um pitch. Design is larger for 1 mm pitch Piezo DM.</td>
</tr>
<tr>
<td>Detectors</td>
<td>Direct Imaging: 1K x 1K visible detector, 12 um (TBR) pixels Low Order Wavefront Sensor: E2V 39, 24 um pixels IFS: 2K x 2K detector, ultra-low noise</td>
</tr>
<tr>
<td>Mechanisms</td>
<td>Shaped Pupil Filter Wheel: 4 position (TBR) Lyot Stop Filter Wheel: 3 position (TBR) Bandpass Filter Wheel: 10 position (TBR) Tip-tilt gimbal: +/- 6 arcsec (TBR), allows for 0.1 arcsec telescope rigid body pointing error). 40 mas resolution. IFS beam splitter mechanism: 2 position Pupil imaging lens wheel: 3 position (TBR) Shaped Pupil x-y stage, 10 um resolution Lyot Stop x-y stage, 10 um resolution Lyot image plane mask wheel, 3 position (TBR) Shutter for FPA</td>
</tr>
</tbody>
</table>
Coronagraph Concept for 19.2 mm DM

- **OAP4**: F/25 occulting focus, RMS WFE < 5 nm
- **Lyot stop**: RMS WFE < 12 nm
- **F/36 focus at FPA**
- **Static DM not at a pupil**
- **Hole in mirror to pass 5x5 arcsec Cass focus**
- **LOWFS**
- **OAP3**: Shaped pupil mask at pupil (flat mirror)
- **OAP2**: Collimator
- **OAP1**: DM/FSM at a pupil

Light from Telescope

Nov 20, 2012
Levine/Shaklan
Coronagraph Concept for 19.2 mm DM

- **OAP 4**: F/36 focus at FPA. Flip in pupil imaging lens.
- **F/25 occulting focus**: RMS WFE < 5 nm.
- **Lyot Stop mask wheel**: And x-y stage.
- **Shutter**: Flip in beam splitter to feed IFS.
- **Occulter mask wheel**: OAP5
- **LOWFS**: OAP2
- **Shaped pupil mask wheel**: And x-y stage.
- **Flip in beam splitter to feed IFS**: FSM Gimbal
- **Hole in mirror to pass 5x5 arcsec Cass focus**
- **DM/FSM at a pupil**
- **COLLIMATOR**: OAP1
- **Light from Telescope**

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**Notes**

- **OAP 4**: F/36 focus at FPA.
- **Lyot Stop mask wheel**: And x-y stage.
- **Shutter**: Flip in beam splitter to feed IFS.
- **Occulter mask wheel**: OAP5
- **LOWFS**: OAP2
- **Shaped pupil mask wheel**: And x-y stage.
- **FSM Gimbal**: OAP3
- **Hole in mirror to pass 5x5 arcsec Cass focus**
- **DM/FSM at a pupil**
- **Collimator**: OAP1

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**Coronagraph Concept for 19.2 mm DM**

**Diagram**

- Scale: 0.24 JPL 22-Oct-12

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**Levine/Shaklan**

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**ExoPlanet Exploration Program**

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**Nov 20, 2012**
Deformable Mirrors for Picometer Aberration Control

Xinetics, 64x64 DM

In hand: several 32x32, one 48x48, One 64x64 currently in use in HCIT
pixel pitch: 1000 um
stroke: ~1.5 um
Mirror segment: glass on PMN

Boston Micromachine 32 x32 MEMS

Phase II SBIR has begun. Delivery of 3000 element continuous facesheet MEMS DM in 2014.
  pixel pitch: 300 um
  stroke: 1.5 um
  Mirror segment material: silicon
Many 32x32 devices in use: Princeton, LLNL, UA, UH, ARC
Lyot Coronagraph: complex mask (amplitude and phase) to address obscured aperture. A monochromatic solution has been found and is shown here. Broad band solution is being addressed.  

*Courtesy of J. Trauger and D. Moody, JPL.*

Shaped Pupil Masks: A binary apodization in the pupil plane is optimized to provide high-contrast attenuation over a prescribed region of the image plane. Naturally broad band, trades IWA, throughput, contrast, and discovery area.  

*Courtesy J. Kasdin and A. Carlotti, Princeton.*
Integral Field Spectrograph

- Follows design principles of ground-based IFS instruments, e.g. CHARIS (Princeton), GPI, SPHERE, OSIRIS
- 140 x 140 lenslet array. Designed to disperse 20% band over 24 detector pixels (SR ~70).
  - Accommodates 0.4 – 1 um range using 4 bandpass filters (one at a time)
  - 17 mas ‘spaxel’ pitch.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Spect. Resol</th>
<th>Species</th>
<th>line depth</th>
<th>At this abundance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.58</td>
<td>5</td>
<td>O3</td>
<td>0.112</td>
<td>3 ppm</td>
</tr>
<tr>
<td>0.69</td>
<td>54</td>
<td>O2</td>
<td>0.088</td>
<td>10%</td>
</tr>
<tr>
<td>0.72</td>
<td>37</td>
<td>H2O</td>
<td>0.13</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>0.73</td>
<td>57</td>
<td>CH4</td>
<td>0.07</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>0.76</td>
<td>69</td>
<td>O2</td>
<td>0.388</td>
<td>10%</td>
</tr>
<tr>
<td>0.79</td>
<td>29</td>
<td>CH4</td>
<td>0.032</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>0.82</td>
<td>35</td>
<td>H2O</td>
<td>0.118</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>0.89</td>
<td>32</td>
<td>CH4</td>
<td>0.417</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>0.94</td>
<td>17</td>
<td>H2O</td>
<td>0.401</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>1.05</td>
<td>40</td>
<td>CO2</td>
<td>0.001</td>
<td>1000 ppm</td>
</tr>
</tbody>
</table>
IFS for Supernova


Table 1: Spectrograph main specifications.

<table>
<thead>
<tr>
<th>Property</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength coverage (μm)</td>
<td>0.4-1.70</td>
</tr>
<tr>
<td>Field of view</td>
<td>3.0&quot; × 3.0&quot;</td>
</tr>
<tr>
<td>Spatial resolution element (arc sec)</td>
<td>0.15</td>
</tr>
<tr>
<td>Spectral resolution, λ/δλ</td>
<td>100</td>
</tr>
<tr>
<td>Cumulative optical throughput</td>
<td>55%</td>
</tr>
</tbody>
</table>

- Longer bandpass, 1.7 vs. 1.0 um
- Coarser pixels, 0.15 vs. 0.017 arcsec
- Higher Spectral resolution, 100 vs. 70
• Allocation for observing a $1 \times 10^{-9}$ contrast planet with systematic-floor limited SNR $= 5$, at $3 \lambda/D$
  
  – Assumes we can start the observation with mean contrast level of $2 \times 10^{-10}$ and std. dev. of $1 \times 10^{-10}$.

  – We determine changes in the state of the system that raise the std. dev to $2 \times 10^{-10}$. This is the final systematic floor.

• Assumes ideal radial band-limited Lyot coronagraph for unobscured aperture.
  
  – A Lyot coronagraph accounting for real pupil will make things worse.

  – A shaped pupil could potentially make things better but it remains to be seen if one can be designed to achieve better than $1 \times 10^{-9}$ residual. Perhaps the DM can ‘dig’ a dark hole in the diffraction pattern.
Top contributors to image plane scatter non-uniformity

Requirement: speckle std. dev. <2e-10 at 3 λ/D

These parameters drift linearly during the observation which may last several hours.

Std. dev. of the amplitude of the linear drift.

Change in image plane uniformity if the given parameter changes by 2x its allocation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Allocation (1 sigma)</th>
<th>dσ</th>
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<tbody>
<tr>
<td>Secondary mirror axial motion</td>
<td>5 nm</td>
<td>5.30E-11</td>
</tr>
<tr>
<td>Telescope rigid body pointing</td>
<td>15 mas</td>
<td>4.90E-11</td>
</tr>
<tr>
<td>Secondary mirror x or y tilt</td>
<td>10 nrad</td>
<td>1.30E-11</td>
</tr>
<tr>
<td>Secondary mirror lateral motion</td>
<td>5 nm</td>
<td>9.00E-12</td>
</tr>
<tr>
<td>Primary mirror coma</td>
<td>10 pm</td>
<td>7.00E-12</td>
</tr>
<tr>
<td>Primary mirror sph. astig.</td>
<td>10 pm</td>
<td>6.00E-12</td>
</tr>
<tr>
<td>Primary mirror focus</td>
<td>30 pm</td>
<td>3.30E-12</td>
</tr>
<tr>
<td>Primary mirror spherical aber.</td>
<td>10 pm</td>
<td>2.20E-12</td>
</tr>
</tbody>
</table>

These allocations may change substantially over the course of the study. Allocations assume low-order wavefront sensor sees only tip-tilt.
Goals:
- Axially and radially separate all 3 channels
- Allow modularity and accessibility for servicing
- Co-locate room-temp Coronagraph & aFGS
- Radially place FPAs outward

Note – what is shown is not original strut configuration,
<table>
<thead>
<tr>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
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<th>Apr</th>
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<td><strong>Coronagraph Design</strong></td>
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<td><strong>Level 1/2 Science Requirements</strong></td>
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<td><strong>Technology Assessment</strong></td>
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<td><strong>Final Report</strong></td>
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- **Coro**
- **IFS**
- **LOWFS**
- **Ops**
- **Yield**
- **Thermal**
- **Instrument**
- **Optical Modlg**
- **Integrated Modlg**
- **Receive WFE & LOS jitter from Thermo-Mech Analyses**
- **Payload Carrier**
- **GSFC Freeze**

ExoPlanet Exploration Program

AFTA Coronagraph Study Schedule
• Main Concerns:
  – Broadband Coronagraph performance w/ obscured telescope
  – Observing Stability: Driven by temperature transients & jitter

• Anticipated technical challenges
  – Coronagraph chromaticity & throughput
  – Impact of increased obscuration for straylight control
  – Observatory operations at cold temperatures
    • telescope materials optimized for room temperature
    • coronagraph operations at RT
  – Orbit: GEO vs L2

• Analyses will provide inputs for future design cycles:
  – Optimize coronagraph for science, stability and straylight
  – Possible improved thermal and vibration multi-stage control
**Ideal Optical Performance of AFTA Coronagraph:**
- Fresnel propagation through all optics including surface errors (figuring, thermal) & WFSC
  - **MACOS** for alignment sensitivities budget verification,
  - **Proper** (J. Krist) for simulation of wavelength dependt speckles & holes around target source

**Thermal-Structural Integrated Analyses:**
- Inputs to MACOS/PROPER from GSFC & JPL traditional STOP analyses
  - Issues w/ meshing, accuracy, active control
  - Demonstration of new ExEP Technology: **CIELO**
    - Single high fidelity model for thermal-structures-optics
    - Temperature dependent material properties, orbit analyses, …
    - Enables direct computation of contrast to transient deformations w/ or w/o active control in the loop: DM WFSC, LOWFS, thermal control.
    - Decomposed into zernickes for direct comparison to error budgets
    - Demonstrated on PECO

*J. Krist, Exopag June 2011*
PECO Integrated Modeling with CIELO

**Streamlined Workflow**

- CAD Geometry, Meshing
- Heat Transfer Analysis
- Temperature Mapping
- Structural Analysis
- Optical Aberrations
- Optical Performance Metrics

**PECO Model:**

- 40K Radiation Exchange surfaces
- 500K Structural degs of freedom

**Example Simulation:**

- 10 degree roll about boresight
- 6 hour Transient response
- Wavefront sensing in the loop

**Contrast from RB Modes (FSM and Wavefront Control):**

**Primary Mirror Response**

**Telescope Temperatures**