Segmented mirror coronagraph study update

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AND

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Apertures for Segmented Coronagraph Design and Analysis (SCDA)

I. Introduction

In support of possible future mission concepts, the Astrophysics Division and the Exoplanet Exploration Program (ExEP) would like to understand the ability of coronagraphs working with segmented and obscured telescope apertures to probe the habitable zones of a large sample of nearby stars and directly image exo-Earths. Reaching contrast ratio levels of $10^{-10}$ at close inner working angles (IWA) to detect the reflected visible light of exo-Earths is an extremely challenging undertaking that has never been achieved experimentally with segmented, obscured apertures in either narrow-band or broadband light.

The first step in achieving this goal is to identify coronagraph designs that work with realistic apertures. This document provides the rationale behind the selection of a set of segmented, obscured apertures, and provides insight into their relative merits based on the current state of the art.

The selected designs are intended to be architecturally representative of the range of apertures that will be considered for a large optical space telescope that performs high-contrast direct imaging using internal coronagraphs. Thus only filled apertures (with the necessary segment gaps) appear. Other forms of direct imaging, e.g. distributed aperture interferometry, are not part of the considered trade space.

The seven apertures defined for this study are shown in Figure 1. To facilitate an “apples to apples” performance comparison, all are designed to be 12 m wide, with 1.68 m (=14%) secondary mirrors (one hexagonal secondary is slightly larger). The secondary diameter was chosen to balance the strong sensitivity of coronagraphs to the size of the central obscuration and to polarization aberrations, with...
Relative challenges of designs under consideration

<table>
<thead>
<tr>
<th>Segment Shape</th>
<th>Max Segm. Dimension</th>
<th>4 ring</th>
<th>3 ring</th>
<th>2 ring</th>
<th>1 ring</th>
<th>Keystone 24</th>
<th>Pie wedge 12</th>
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<tr>
<td>Pie wedge</td>
<td>5 m x 3.14 m</td>
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<td>Pie wedge</td>
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Launch Configuration
- Segments
- Backplane
- Stability
- SM Support

Overall Ranking

Table 1: Relative challenges of designs under consideration.

This document discusses these challenges. All apertures are deemed "buildable" though some will require significant new infrastructure including fabrication and potentially test facilities, and some will be significantly more challenging to build, test, and deploy.

II. Segment Configuration
The segment configurations define a range from JWST-like hex segments of various sizes to keystone and pie wedge shapes as seen in Figure 1. It should be noted that for the purposes of this initial study, the team has assumed that Corning ULE® glass or a glass ceramic such as Schott Zerodur or Ohara Clearceram are the most likely material choices for the mission given the high quality mirror surfaces required combined with the very low CTE and high stability characteristics inherent in these types of mirror assemblies.
Throughput vs starlight suppression

G. Ruane et al. 2016, in prep

How much throughput should be sacrificed for starlight suppression?

- Designed starlight suppression
- Maximum throughput

Best case (far off-axis)
Energy within $0.7 \lambda / D$
Normalized to telescope
Relevant metric: integration time

G. Ruane et al. 2016, in prep

Ground

TMT in K band: $\Phi_p / \Phi_s = 10^{-6}$

$$\Delta t \propto s / \eta_c^2$$

$$\Delta t \propto 1 / \eta_c^2$$

1000 hr 100 hr 10 hr

Relative throughput, $\eta_c / \eta_0$

Designed starlight suppression, $s$

Space

LUVOIR in V band: $\Phi_p / \Phi_s = 10^{-10}$

$$\Delta t \propto s / \eta_c^2$$

1000 hr 100 hr 10 hr

Relative throughput, $\eta_c / \eta_0$

Designed starlight suppression, $s$
Situated on a future flagship space observatory offers a promising avenue to fulfill this vision (Delcanton et al., 2015). One NASA mission concept that could serve as the platform to realize this scientific breakthrough is the Large UV/Optical/IR Surveyor (LUVOIR). LUVOIR is envisioned to use a large, segmented mirror to achieve a significant gain in collecting area and angular resolution over both the Hubble Space Telescope and the James Webb Space Telescope. Such a mission would address a broad range of topics in astrophysics with a multi-wavelength, serviceable suite of instruments.

In support of the research community’s assessment of the scientific capability of a LUVOIR mission, the Exoplanet Exploration Program (ExEP) has organized a new technical study, Segmented Coronagraph Design and Analysis (SCDA) (Siegler, 2016; Feinberg et al., 2016). The goal of SCDA is to further our understanding of the ability of coronagraphs to operate with segmented/obscured apertures and image terrestrial analogs in the habitable zones of nearby stars. The results of the SCDA effort will directly inform the mission concept evaluation being carried out by the LUVOIR Science and Technology Definition Team.

The apodized pupil Lyot coronagraph (APLC; Aime et al., 2002; Soummer et al., 2003; Soummer, 2005; Soummer et al., 2009, 2011) is one of several coronagraph design families that SCDA will assess, in particular the recent hybrids replacing graded-transmission apodizers with binary-transmission shaped pupils. The APLC is a Lyot-style coronagraph that suppresses starlight through a series of amplitude operations on the on-axis field (Aime et al., 2002; Soummer et al., 2003; Soummer, 2005; Soummer et al., 2009, 2011).

A diagram of the APLC concept is shown in Figure 1. The mask architecture combines an entrance pupil apodization in plane A, a downstream focal plane mask (FPM) in plane B, and the Lyot stop in the relayed pupil plane C to form the coronagraphic image on a detector located in the re-imaged focal plane D.

Figure 1: Conceptual diagram for the apodized pupil Lyot coronagraph (APLC). In the APLC design simplified on current ground-based observatories, the transmission profile of an apodizer inserted in plane A is optimized so that the two scalar field components of the field in the Lyot plane \( \psi_c(r) \) approximately cancel.

The APLC is one of the leading coronagraphs in the current generation of ground-based instruments. It is used in VLT/SPHERE, Palomar P1640, and Gemini Planet Imager (GPI) (Beuzit et al., 2008; Hinkley et al., 2011; Macintosh et al., 2014) to directly image young giant planets, including the recent discovery of 51 Eri b (Macintosh et al., 2015). The GPI APLC, for example, is designed to reach a raw contrast of \( 2 \times 10^{-8} \) at 0.2 arcsec in 20% broadband light, and in the presence of central obstructions and support structures.
APLC designs

Figure 4: Example APLC apodizers produced by the hexagonal survey for various focal mask radii and telescope apertures. These designs produce annular, contrast dark zones with working angle range $5\omega_0 - 10\omega_0$ over a $2\omega$ bandpass.

Energy in the half-max region of the off-axis (unocculted) coronagraph planet PSF, and the energy incident on the telescope primary mirror. The relative core throughput is the ratio of energy in the core of the half-max region of the off-axis (unocculted) coronagraph PSF, normalized to the energy in the half-max region of the telescope PSF without a coronagraph. Without a coronagraph, the core of the segmented telescope PSF encircles roughly half of the total integrated energy; therefore the core throughput is generally close to half of the relative core throughput.

The solutions at FPM radius $4 \omega_0$ show a poorer quality in terms of how close the solution approaches to the desired binary-transmission profile. This is evident in the gray regions that appear in the apodizer arrays in Figure 4. As a consequence, their corresponding throughput metrics are less reliable than for the $5 \omega_0$ and $6 \omega_0$ cases. Improving the apodizers' solutions at this lower extreme of the APLC working angle range will require modifications to the Gurobi solver parameters and/or propagation model spatial resolution.

There are few trends worth noting in the throughput tables. First, the large jump in throughput between FPM radius $4 \omega_0$ and $5 \omega_0$ appears consistently for all telescope apertures and bandwidths. This suggests that the most efficient FPM radius in terms of scientific survey yield would most likely lie in between. Conversely, little to no gain is found by increasing the FPM radius above $5 \omega_0$.

At FPM radius $5 \omega_0$ and above, there is only a marginal difference in the throughput performance between the 'Hex 3', 'Hex 4', and 'Hex 5' apertures: the APLC core throughputs match within $2\omega$. For the same FPM radii, however, the 'Hex 2' solutions are generally worse. The unique profile of the 'Hex 2' aperture
APLC raw contrast

Figure 5: Example numericalevaluation of a survey solution: The on-axis PSF in the final image plane of the coronagraph, with no wavefront errors and no wavefront control. Shown here is the PSF of a 21% bandpass APLC solution for the 'Hex 5' telescope aperture and FPM radius 5. The inner and outer bounds of the coronagraph field of view are marked by two dashed circles, with radii 5 and 21.

The effect of segment gap width and telescope feature padding

We also examined the effect of augmented obscuration/gap features on the APLC solution throughput. A cursory study of this relationship is important for two reasons. First, it reveals the impact of building in tolerance to errors in the assumed telescope pupil, as well as errors in the apodizer mask alignment. Second, it indicates how APLC performance is affected by the width of segment gaps and secondary support struts.

For these tests, we restrict the points in the apodizer array that are allowed to be optimized based on a binary-valued representation of the telescope pupil. Where the binary telescope mask is clear (full transmission), the apodizer is optimized as a free variable. Conversely, where the binary telescope mask is dark (zero transmission), the apodizer transmission is fixed at zero.

The optimized apodizer array is 500 points in diameter (twice the size of the pupil size used in Section 4).

Before scaling the telescope aperture mask down to the optimization size, we pad the telescope features using a 3-D shift-and-multiply loop, which darkens pixels adjacent to any obscuration present in the reference telescope aperture. The level of padding is parametrized by a radius of enabled shifts. We specify three levels of padding, illustrated in Figure 6 for the 'Hex 5' telescope case:

• At 'Level 2', the features closely approximate the reference aperture and the minimum segment gap width at 6 > 611 is 2 pixel > 1/3 of pupil diameter (equivalent to 3/5 cm for the nominal 23-meter primary diameter).
### APLC throughput

#### 10% BW

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<th>FPM rad. ($\lambda_0/D$)</th>
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<th>Hex3</th>
<th>Hex4</th>
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<tr>
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<td>rel.</td>
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<td>rel.</td>
<td>rel.</td>
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<td>7.0%</td>
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<tr>
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<td>16.0%</td>
<td>14.6%</td>
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<tr>
<td></td>
<td>37.1%</td>
<td>42.1%</td>
<td>41.4%</td>
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#### 15% BW

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<th>Hex3</th>
<th>Hex4</th>
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<td>41.9%</td>
<td>41.4%</td>
<td>40.7%</td>
</tr>
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</table>
Apodizer manufacturing challenges

Figure 12: Azimuth averaged intensity profile of the coronagraphic image reached by an APLC solution in 21% broadband light with a quasi-binary shaped pupil. Profiles are represented for the design with the original gray version (blue) and the binarized version (orange) using error diffusion algorithm (EDA; e.g., Dorrer & Zuegel, 2007) with a lateral size $\overline{\alpha} > 23611$ obtained by sub-pixelization of the original design gray pixels. The dashed black vertical lines delimit the high-contrast dark zone (between $4/6$ and $21\alpha_{10}$). The red dotted line delimits the FPM radius, set to $5\alpha_{10}$. The averaged contrast over the spectral band in the dark region is below $21\omega_{21}$ (black horizontal line). The $21\omega_{21}$ contrast performance of the original design is almost recovered with an EDA version using $\overline{\alpha} > 23611$. Relating current black silicon technologies to a manufacture shaped pupil mask for WFIRST coronagraph, we translate these values into physical units. Assuming a $6\alpha_{m}$ size for a pixel, the apodizer of our design can currently be fabricated with a $73/6\alpha_{m}$ diameter prototype to work in visible light.

Acknowledgements

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References

Team UoA/AMES/JPL: Phase Induced Amplitude Apodized Complex Mask Coronagraph

PIAACMC concept achieves starlight suppression by combining:
- Lossless apodization with aspheric optics (PIAA)
- Creates PSF with weak Airy rings
- Focal plane mask complex amplitude \(-1 < t < 0\)
- Induces destructive interference inside downstream pupil
- Lyot Stop blocks starlight

PIAACMC does not care about pupil geometry: segments, spiders, central obstruction OK

University of Arizona/AMES/JPL: O. Guyon, J. Codona, R. Belikov, B. Kern
Complex Phase Mask Coronagraph: mask design

~1 wave PTP, $d \sim 3 \lambda/D$
Current PSF contrast
(point source, monochromatic)

contrast: 2.8e-9 average in 1.5-8 l/D zone
... currently optimizing PIAA shape to improve

10% BW(*)

wide view:
0.17% of starlight scattered by high spatial frequency noise
Team Caltech/JPL:
Apodized vortex (and HLC)

- **Caltech**: Garreth Ruane, Dimitri Mawet
- **JPL**: Jeff Jewell, Stuart Shaklan
Apodized vortex design

- Start with ring-apodized vortex (RAVC) analytical solution (Mawet et al. 2013)

- Finish off with a new, game-changing method invented by Jeff Jewell (JPL): Auxiliary Field Conjugation
Optimization procedure

\[ \min_w \left( \left\| QCw \right\|^2 + b \left\| w - E_{\text{pup}} \right\|^2 \right) \]

Algorithm:
1. Solve for pupil field that will create the specified dark hole:
   \[ w = \left( bI + C^\dagger QC \right)^{-1} bE_{\text{pup}} \]
2. Apply constraints set by optical system to \( A = |w| \):
   \[ 0 \leq A \leq 1 \]
   \[ \text{supp}\{A\} = \text{supp}\{P\} \]
3. Set \( E_{\text{pup}} = PA \), and repeat

\( C \) – coronagraph propagation operator
\( Q \) – dark hole region
\( w \) – auxiliary field
\( b \) – regularization parameter
\( E_{\text{pup}} \) – current pupil field
\( A \) – gray-scale apodizer
\( P \) – original pupil field

Aux. field conjugation algorithm developed by Jeff Jewell, JPL
Apodized vortex solutions for SCDA pupils

Solutions are wavelength independent!
Apodized vortex solutions for SCDA pupils

-1 -0.5 0 0.5 1

\( x/R \)

-1 -0.5 0 0.5 1

\( y/R \)

10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}

Angular coordinate (\( \lambda/D \))

10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5}

On-axis PSF (az. avg.)

Angular separation (\( \lambda/D \))

Normalized to telescope

Throughput

12% at 3 \( \lambda/D \)

Normalized to telescope

10 15 20

Angular coordinate (\( \lambda/D \))

12% at 3 \( \lambda/D \)

Normalized to telescope

Total energy

Energy within 0.7 \( \lambda/D \)

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Using the DMs to generate phase-induced apodization of spiders

Clippedhex4 w/ 10cm spiders, VC4 (no apod.), Dark hole: 3-10 $\lambda/D$ annulus, $z = 300\text{mm}$, $F = 56$, 10% bandwidth (3$\lambda$'s), 500 iterations
Doubles throughput

Clipped hex4 w/ 10cm spiders, VC4 (no apod.), Dark hole: 3-10 $\lambda/D$ annulus, $z = 300$mm, $F = 56$, 10% bandwidth ($3\lambda$’s), 500 iterations
Central obscuration limits the throughput

Sensitivity to central obscuration

- Total energy
- within 0.7 λ/D

charge 4 RAVC
3-5 λ/D average

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Unobscured, segmented telescopes
Scientific motivation for larger apertures
Wang, Mawet, Ruane, Hu, Benneke 2016, in preparation

SNR in the spectral resolution vs starlight attenuation space (tint = 100 hr)

- Impact on telescope architecture: relax contrast requirements, thus stability
- Impact on instrument architecture: IFS or imager + classical high-R spectrograph
Scientific motivation for larger apertures
Wang, Mawet, Ruane, Hu, Benneke 2016, in preparation

Figure 9. Albedo spectrum of an Earth-like planet. We consider the average albedo between a high cloud case (high albedo) and no cloud case (low albedo). Shaded regions are wavelength regions we consider to simulate observations for detecting molecular species.

Figure 10. Factors normalized by their maximum values for CO$_2$, O$_2$, and H$_2$O over wavelengths ranging from 0.5 to 1.7 \(\mu\)m.

Figure 11. Factors normalized by their maximum values for CH$_4$, CO$_2$, O$_2$, and H$_2$O over wavelengths ranging from 0.5 to 2.175 \(\mu\)m.

5.2.1. Simulating LUVOIR Observation
A Large ultraviolet, optical and infrared (LUVOIR) telescope is a candidate for next-generation space telescope (10-m class). Exoplanet study will be one of its major scientific objectives. Based on calculations in §5.1, we consider a filter centered at 0.7 \(\mu\)m for O$_2$ detection and a filter centered at 1.5 \(\mu\)m for CO$_2$ and H$_2$O detection. Both filters have a bandwidth of 20%. We consider an optimistic case in which detector noise (both readout noise and dark current) is set to zero, and a baseline case in which detector noise is set to values that can be currently achieved. Table 4 and 5 summarize the parameters used in simulation.

Unlike the case for HR 8799 e and 51 Eri b, we consider only photon noise limited case. At low SNR regime, which is the case for Earth-like planet observation, CCF SNR is unlikely to be limited by CCF fluctuation, which can only be seen at high SNR regime. At low SNR regime, LSD is not likely to be effective because decomposition tends to introduce noise and further decrease the SNR. Since we use the same albedo spectrum for the input planet spectrum and the template spectrum for cross correlation, there is no mismatch spectrum case. Therefore, the results shown below should be interpreted...
Clippedhex4 w/o central obscuration

Max. throughput = 76% (PSF core relative to telescope).
Clippedhex3 w/o central obscuration

Max. throughput = 76% (PSF core relative to telescope).
Clippedhex2 w/o central obscuration

Max. throughput = 78% (PSF core relative to telescope).
Using the DMs to generate phase-induced apodization of segment gaps

• Gain additional ~5-10% in throughput, approach lossless coronagraph (>80% throughput)
Clippedhex4 w/ central obscuration and ring apodizer (for comparison)

Max. throughput = 21% (PSF core relative to telescope).
Piewedge8 w/ central obscuration and ring apodizer (for comparison)

Max. throughput = 37% (PSF core relative to telescope).
Band-limited coronagraphs: work in progress
Band-limited coronagraphs: work in progress
Band-limited coronagraphs: work in progress

Dark hole degrades with bandwidth

optimized for 3-5 $\lambda/D$
Conclusions relevant to HabEx

• There are high-contrast coronagraph solutions for obscured, segmented telescopes

• Throughput is key, more important than starlight suppression

• Unobscured, segmented apertures are coronagraph friendly and much higher throughput (factor ~2 to 4)

=> up to factor 10 in integration time
TBD

- Consolidate unobscured segmented coronagraph designs (APLC, PIAACMC)
- Sensitivity to segment phasing and gap sizes and shapes?
- Tolerancing to alignment
- Manufacturing errors of apodizers and focal plane masks