Apodization Methods for Vortex Coronagraphs on Segmented Aperture Space Telescopes

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Three-mask coronagraph concept

Coronagraphs are designed to:
1. Passively suppress starlight
2. Maximize signal from planets
Vortex coronagraph for unobscured telescopes

Light from point source rejected by Lyot stop for even (nonzero) charges.
Performance with *unobscured* telescopes

1. Insensitivity to finite size of star (and jitter).
2. High throughput at small angular separations.

Residual starlight (ideal)

For ideal optical system, 0.1 \( \lambda/D \) source sufficiently suppressed for charge 6+

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Charge 4
Charge 6
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“Planet” throughput

Possible to image planets at \( \leq 3 \lambda/D \)

Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.

Throughput is defined as energy within 0.7 \( \lambda/D \) of the source position, normalized to that of the telescope.

Performance with *unobscured* telescopes

3. Insensitivity to low order aberrations.

Residual starlight with $\lambda/1000$ rms wavefront error

**Charge 4**

- Insensitive to defocus
- Astigmatism, coma, and trefoil

**Charge 6**

- Insensitive to defocus, astigmatism, coma, and spherical

Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.

Zernike mode selection rules

For small phase aberration i.e. $\Phi \ll 1$ rad

$$\exp(i\Phi) \approx 1 + i\Phi$$

$$\Phi = Z_n^m(r, \theta)$$

Zernike mode is rejected if:

- $l$ is even
- $|l| > n + |m|$

VC rejects $(l/2)^2$ Zernike modes to first order

e.g. Charge 6 rejects astigmatism

on-axis point source, perfect wavefront

Real or imaginary part:

Astigmatism

Phase mask

Lyot plane

Lyot stop

Can we take advantage of these benefits on segmented apertures?

SCDA study, led by Stuart Shaklan (JPL), supported by the Exoplanet Exploration Program (ExEP).
Apodization approaches

Option #1: Apodizing pupil mask (e.g. Shaped pupil, APLC, APP, etc.)

Option #2: Beam shaping with DMs (e.g. WFIRST Lyot coronagraph)
Grayscale apodized vortex coronagraph

on-axis point source, perfect wavefront

Apodizer (in pupil)  Focal plane mask  Lyot stop (in pupil)

Apodizer  Focal plane mask  Field mag. before LS  Lyot stop (LS)

(a)  \( A \)  \( \Omega \)  \( \Theta \)

\[ \exp(i2\phi) \]

\[ \exp(i4\phi) \]

Grayscale apodized vortex coronagraph

Pupil

Apodizer

Lyot stop

Stellar irradiance

Ruane et al., *Proc. SPIE* 99122L (2016)
Auxiliary field optimization: gray-scale apodizers

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

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 optimization algorithm developed by Jeff Jewell, JPL
A family portrait of apodizer designs
Performance for off-axis segmented telescopes

hex3: 3-ring hexagonally segmented primary (37 segments)

1. Insensitivity to finite size of star and jitter maintained.
2. Apodizer introduces a throughput loss.

Throughput loss owing to:
1. circularized aperture
2. apodization pattern
Performance for off-axis segmented telescopes

hex3: 3-ring hexagonally segmented primary (37 segments)

Pupil charge 4 charge 6 charge 8 Lyot stop

3. Insensitivity to Zernike aberrations maintained.

Residual starlight with λ/1000 rms wavefront error

Charge 6
Improving designs for on-axis telescopes

• **Compounding issues with current on-axis designs:**
  1. Decreased throughput.
  2. More sensitivity to the finite size of the star.
  3. Large $D$ means $\lambda/D$ is smaller with respect to the star.

• **Updating optimization procedure to combat these effects.**

• **Several approaches have yet to be considered:**
  • Gray-scale apodizers with updated metrics
  • Lyot stop optimization
  • Focal plane mask optimization
  • Beam shaping with DMs
  • Multiplexed sub-apertures
Auxiliary field optimization: beam shaping

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

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. Determine the DM surfaces that achieve the best match between \( E_{\text{pup}} \) and the target field \( w \).
3. Repeat steps 1 and 2 until sufficient starlight suppression is obtained.

Aux. field optimization algorithm developed by Jeff Jewell, JPL
Beam shaping with central obscuration

Solution obtained via “Auxiliary Field Optimization” (Jewell et al., in prep.)
Beam shaping without central obscuration

Solution obtained via “Auxiliary Field Optimization” (Jewell et al., in prep.)
Throughput comparison

Relative throughput (within $0.7\lambda/D$)

Angular separation ($\lambda/D$)
Summary

- Current vortex coronagraph designs perform well with an off-axis telescope (even if segmented).

- Designs for on-axis telescopes are currently limited by sensitivity to finite size of stars.

- Optimization approach to be tailored to the finite size of stars, especially for large on-axis telescopes.

- Apodization by means of beam shaping with deformable mirrors is a pathway to higher throughput.

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