Electric field reconstruction in the image plane of a high-contrast coronagraph using a set of pinholes around the Lyot plane

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Progress

Time

Your SPIE talk

Monday, June 25, 2012
The night before your talk

Monday, June 25, 2012
Your SPIE talk

The night before your talk

Monday, June 25, 2012
The night before your talk
Electric Field Conjugation

DM plane

Plane of interest

\[ E_{abr + ideal} \]

\[ E_f = \]

Monday, June 25, 2012
Electric Field Conjugation

DM plane

Plane of interest

\[ E_f = E_{abr+ideal} \]
$E_f = E_{ab} + i\text{deal}$
Electric Field Conjugation

\[ E_f = E_{abr+ideal} + E_{DM} \]
Find the shape of the DM such that its effect in the plane of interest negates the electric field present in this plane due to the coronagraph and the aberrations.

\[ E_f = E_{abr+ideal} + E_{DM} = 0 \]
Electric Field Conjugation

Find the shape of the DM such that its effect in the plane of interest negates the electric field present in this plane due to the coronagraph and the aberrations.

\[ E_f = E_{abr+ideal} + E_{DM} = 0 \]

Linearize w.r.t actuators heights.
What shapes on the DM should we use for the probes?
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\[ DM(x, y) = ? \]
What shapes on the DM should we use for the probes?

\[ DM(x, y) = \text{sinc}(w_x x) \text{sinc}(w_y y) \]
What shapes on the DM should we use for the probes?

\[ DM(x, y) = \text{sinc}(w_x x) \text{sinc}(w_y y) \cos(f_x x + \phi) \]
What shapes on the DM should we use for the probes?

\[ DM(x, y) = \text{sinc}(w_x x) \text{sinc}(w_y y) \cos(f_x x + \phi) \]
DM voltages

Measured intensity
DM voltages → Probe images → Measured intensity
DM voltages
Probe images
Measured intensity

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DM voltages

Probe images

Measured intensity

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DM voltages

Probe images

Real and imaginary parts of the estimated Electric field

Measured intensity

Difference

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Take an image

Calculate average intensity in the control region

Take probe images

Reconstruct the electric field in the image plane

Simulate the non-linear system

Apply new DM settings
Measurements were taken at 2% around 800nm

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Measurements were taken at 2% around 800nm
Take an image

Calculate average intensity in the control region

Take probe images

Reconstruct the electric field in the image plane

Simulate the non-linear system

Apply new DM settings

Measured image

Probe images

Measurements were taken at 2% around 800nm

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Measurement image

Intensity from reconstructed electric field

Measurements were taken at 2% around 800nm

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After one iteration

After five non-linear analytic sub-steps

Take an image

Calculate average intensity in the control region

Take probe images

Reconstruct the electric field in the image plane

Simulate the non-linear system

Apply new DM settings

Measured image

Measurements were taken at 2% around 800nm

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Take an image

Calculate average intensity in the control region

Take probe images

Reconstruct the electric field in the image plane

Simulate the non-linear system

Apply new DM settings

Measured image

Change in DM actuators

Measurements were taken at 2% around 800nm

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Measurements were taken at 2% around 800nm
Results in various labs

Laboratory for Adaptive Optics
UC Santa-Cruz

High Contrast Imaging Testbed
Jet Propulsion Laboratory

Best dark hole to date has mean intensity $3.5 \times 10^{-8}$
Region is $2 < x / (\lambda D)_{sky} < 4$, $-4 < y / (\lambda D)_{sky} < 4$
Inner edge of dark hole $2.05 (\lambda D)_{sky}$

Give’on et al 2008, Thomas et al 2010

Kern et al SPIE 8151, 2011

Trauger et al SPIE 8151, 2011

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Incoherent? or Uncontrollable? or?

This can be due to inability to resolve changes over time, space or polarization (in between exposures of the probes).

However, this can also be due to errors in the model of the system (probes).
Light in the Lyot plane

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The Peek-a-Boo estimation method

Rather than changing the DM, we let light through a pinhole at a different location each time
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The Peek-a-Boo estimation method

Rather than changing the DM, we let light through a pinhole at a different location each time
The Peek-a-Boo estimation method

Rather than changing the DM, we let light through a pinhole at a different location each time
Choosing the locations of the pinholes
Choosing the locations of the pinholes
Simulations with photon noise

1 Photon per 1e-8 contrast

1 Photon per 1e-9 contrast
Selecting the pinholes

<table>
<thead>
<tr>
<th>State</th>
<th>X pos.</th>
<th>Y pos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
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Selecting the pinholes

<table>
<thead>
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<th>X pos.</th>
<th>Y pos.</th>
</tr>
</thead>
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<td>0</td>
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Selecting the pinholes

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<th>Y pos.</th>
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<td>1</td>
<td>-1</td>
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Selecting the pinholes

<table>
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<th>Y pos.</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>-2</td>
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Selecting the pinholes

<table>
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<th>Y pos</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>1</td>
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Selecting the pinholes
Selecting the pinholes

<table>
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<th>X pos.</th>
<th>Y pos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2</td>
<td>-1</td>
</tr>
</tbody>
</table>
\[
\begin{align*}
I_0 &= |E_0|^2 + I_{inc} \\
I_{oa} &= |E_0 + E_a|^2 + I_{inc} \\
I_{ob} &= |E_0 + E_b|^2 + I_{inc} \\
I_{oc} &= |E_0 + E_c|^2 + I_{inc} \\
I_{od} &= |E_0 + E_d|^2 + I_{inc}
\end{align*}
\]

\[
\begin{bmatrix}
\Re\{E_0\} \\
\Im\{E_0\}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
-\Im\{E_a\} & \Re\{E_a\} \\
-\Im\{E_b\} & \Re\{E_b\} \\
-\Im\{E_c\} & \Re\{E_c\} \\
-\Im\{E_d\} & \Re\{E_d\}
\end{bmatrix} \begin{bmatrix}
I_{oa} - |E_a|^2 \\
I_{ob} - |E_b|^2 \\
I_{oc} - |E_c|^2 \\
I_{od} - |E_d|^2
\end{bmatrix}
\]
Calibration model

\[
\begin{align*}
I_a &= |E_a|^2 \\
I_b &= |E_b|^2 \\
I_c &= |E_c|^2 \\
I_d &= |E_d|^2 \\
I_{ab} &= |E_a + E_b|^2 \\
I_{ac} &= |E_a + E_c|^2 \\
I_{ad} &= |E_a + E_d|^2 \\
I_{bc} &= |E_b + E_c|^2 \\
I_{bd} &= |E_b + E_d|^2 \\
I_{cd} &= |E_c + E_d|^2
\end{align*}
\]
RMS improvement

Model-based calibration

Measurement-based calibration

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Summary

- The pair-wise estimation has been used now on various testbeds with different coronagraphs with the best contrast results to date.

- Pinholes estimate has been implemented and ready to be tested in closed loop correction

- Pinholes estimate offers an independent method

- We hope to improve the calibration process to gain better estimates