Telescope Pupil Tracking using a Pyramid WFS

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Pupil planes and pupil relays

Telescope pupil (M1 or M2)

AO Deformable Mirror

WFS pupil plane

Science Instrument Lyot Stop

Pupil Relay (Telescope)

Pupil Relay (AO WP)
DM / WFS mis-registration

Telescope pupil (M1 or M2)

AO Deformable Mirror

WFS pupil plane

Science Instrument Lyot Stop

Pupil Relay (Telescope)

Pupil Relay (Science)
DM / Lyot stop mis-registration

Telescope pupil
(M1 or M2)

AO Deformable Mirror

Pupil Relay
(Telescope)

WFS pupil plane

Pupil Relay
(Science)

Science Instrument
Lyot Stop
DM / Lyot stop mis-registration

Telescope pupil (M1 or M2)

Pupil Relay (Telescope)

Ground Deformable Mirror

High-altitude Deformable Mirror

Pupil Relay (Science)

WFS pupil plane

Science Instrument Lyot Stop

Pupil Viewing Camera
Wave-front @ M1 (D=30m)
After propagation, the high spatial frequencies of amplitude have turned into phase.
Wavefront @ DM11 after adding 1.5um P-V waffle on DM11

Amplitude does not change

Waffle added to phase
Wavefront propagated back to pupil (-11.8km propagation)

Amplitude

Phase

High spatial frequencies of waffle pattern have propagated to amplitude

Phase still largely contains waffle, with slightly increased amplitude
Telescope / WFS / Lyot mis-registration

Telescope pupil (M1 or M2)

AO Deformable Mirror

Pupil Relay (Telescope)

WFS pupil plane

Science Instrument Lyot Stop

Pupil Relay (Science)

Pupil Viewing Camera
TMT Pupils: full resolution and 24x24 binning
Pupil image at PWFS

- 4 pupil images, each sampled by 96x96 pixels
- Sum the four images to reconstruct full pupil images
- Pupil images at the PWFS is blurred by various effects:
  - Charge diffusion @ CCD
  - Image quality of optical relay
  - Diffraction of 2” field stop
  - FSM not exactly at pupil plane (share with ADC)
- Blurring kernel has 1 pixel FWHM
Pupil images with blurring:
Full resolution and 24x24 binning
Flux assumptions

- zeroPointR = 1.35e10; photons/m^2/s
- area = 15.^2*π; TMT collecting area
- tp = 0.424; throughput to WFS (QE=94%)
- back = 660e3; photons/s/arcsec^2 (bright time)
- back = 66e3; photons/s/arcsec^2 (dark time)
- back = back * 1 * π^2; Through 2" field stop
- rn = 1 electron; read-noise

- Segment reflectivity non-uniformity:
  - ±3% throughput for each segment (Larry Stepp)
Pupil position estimation algorithms

• Pupil position is estimated from pupil image obtained from PWFS.
• Assumed magnitude: $m_R = 18.5$
• Assumed integration time: 0.33s
  ◦ Most of the photons come from background
• Assumed 24x24 (x4) binning
• Algorithms:
  ◦ Center of gravity
  ◦ Correlation + center of gravity
  ◦ Unconstrained matched filter
    ◦ Derivatives can be obtained numerically or optically using pupil steering mirrors in VNW
Matched filters
Pupil image at the PWFS
60x60 pixel resolution

Geometric image

PWFS 5λ/D
PWFS 10λ/D
PWFS 20λ/D
PWFS 40λ/D
Pupil image at the PWFS
30x30 pixel resolution

Geometric image

PWFS 5λ/D
PWFS 10λ/D
PWFS 20λ/D
PWFS 40λ/D
Pupil image of star at the PWFS
20x20 pixel resolution

<table>
<thead>
<tr>
<th>Geometric image</th>
<th>PWFS 5λ/D</th>
<th>PWFS 10λ/D</th>
<th>PWFS 20λ/D</th>
<th>PWFS 40λ/D</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Geometric image" /></td>
<td><img src="image2.png" alt="PWFS 5λ/D" /></td>
<td><img src="image3.png" alt="PWFS 10λ/D" /></td>
<td><img src="image4.png" alt="PWFS 20λ/D" /></td>
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<td><img src="image6.png" alt="Geometric image" /></td>
<td><img src="image7.png" alt="PWFS 5λ/D" /></td>
<td><img src="image8.png" alt="PWFS 10λ/D" /></td>
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<td><img src="image13.png" alt="PWFS 10λ/D" /></td>
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<td><img src="image18.png" alt="PWFS 10λ/D" /></td>
<td><img src="image19.png" alt="PWFS 20λ/D" /></td>
<td><img src="image20.png" alt="PWFS 40λ/D" /></td>
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Bright time results 1
mR=18.5, IT=0.33

- Monte-Carlo simulation
- 10,000 trials
- Photon + read-out noise but no segment throughput fluctuations

<table>
<thead>
<tr>
<th></th>
<th>Circular pupil</th>
<th>TMT Pupil 1</th>
<th>TMT Pupil 2</th>
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<tr>
<td></td>
<td>RMS-x</td>
<td>RMS-y</td>
<td>RMS-x</td>
</tr>
<tr>
<td>Centroid</td>
<td>0.0260%</td>
<td>0.0259%</td>
<td>0.0255%</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.0260%</td>
<td>0.0259%</td>
<td>0.0255%</td>
</tr>
<tr>
<td>Matched filter</td>
<td>0.0089%</td>
<td>0.0089%</td>
<td>0.0088%</td>
</tr>
</tbody>
</table>

RMS error with matched filter~ 0.01 %
Bright time results 2
mR=18.5, IT=0.33

- Monte-Carlo simulation
- 10,000 trials
- No Photon + read-out noise but with segment throughput fluctuations

<table>
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<tr>
<td></td>
<td>RMS-(x)</td>
<td>RMS-(y)</td>
<td>RMS-(x)</td>
</tr>
<tr>
<td>Centroid</td>
<td>0.0202%</td>
<td>0.0198%</td>
<td>0.0204%</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.0202%</td>
<td>0.0198%</td>
<td>0.0204%</td>
</tr>
<tr>
<td>Matched filter</td>
<td>0.0043%</td>
<td>0.0043%</td>
<td>0.0048%</td>
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RMS error with matched filter~ 0.005%
### Dark time results

**mR=18.5, IT=0.33**

#### Photon + read-out noise but no segment throughput fluctuations

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<td><strong>RMS-x</strong></td>
<td></td>
<td></td>
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<tr>
<td>Centroid</td>
<td>0.0669%</td>
<td>0.0654%</td>
<td>0.0659%</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.0669%</td>
<td>0.0654%</td>
<td>0.0659%</td>
</tr>
<tr>
<td>Matched filter</td>
<td>0.0221%</td>
<td>0.0216%</td>
<td>0.0208%</td>
</tr>
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</table>

#### RMS error with matched filter ~ 0.022 %

#### No Photon + read-out noise but with segment throughput fluctuations

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<tr>
<td>Centroid</td>
<td>0.0202%</td>
<td>0.0204%</td>
<td>0.0204%</td>
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<tr>
<td>Correlation</td>
<td>0.0202%</td>
<td>0.0204%</td>
<td>0.0204%</td>
</tr>
<tr>
<td>Matched filter</td>
<td>0.0040%</td>
<td>0.0045%</td>
<td>0.0049%</td>
</tr>
</tbody>
</table>

#### RMS error with matched filter ~ 0.005% (same as bright time)
Use a unique matched filter?

In principle, matched filter must be recomputed as spiders rotate.
Can we use the matched filter computed with annular pupil for all spider orientations?
Annular pupil matched filter has a lower gain.
Gain can be adjusted (x1.8) to provide unity gain at the origin.
Dark time results
Annular pupil matched filter

Photon + read-out noise but no segment throughput fluctuations

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<tr>
<td>Matched filter</td>
<td>0.0221%</td>
<td>0.0218%</td>
<td>0.0247%</td>
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</table>

RMS error with matched filter~ 0.028 %

No Photon + read-out noise but with segment throughput fluctuations

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<td>0.0204%</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.0202%</td>
<td>0.0198%</td>
<td>0.0204%</td>
</tr>
<tr>
<td>Matched filter</td>
<td>0.0037%</td>
<td>0.0036%</td>
<td>0.0040%</td>
</tr>
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</table>

RMS error with matched filter~ 0.005% (same as before)
Summary

- Matched filter provides significantly more accurate pupil position estimate than centroid or correlation

- Pupil position error
  - 0.010% RMS of pupil diameter (0.022% in dark time)
  - Background contributes useful photons

- Non-uniformity of M1 segments reflectivity
  - 0.005% RMS of pupil diameter

- Annular pupil matched filter
  - Modest increase of estimation error (0.022% to 0.028%)
  - Much more convenient