Telescope Pupil Tracking using a Pyramid WFS

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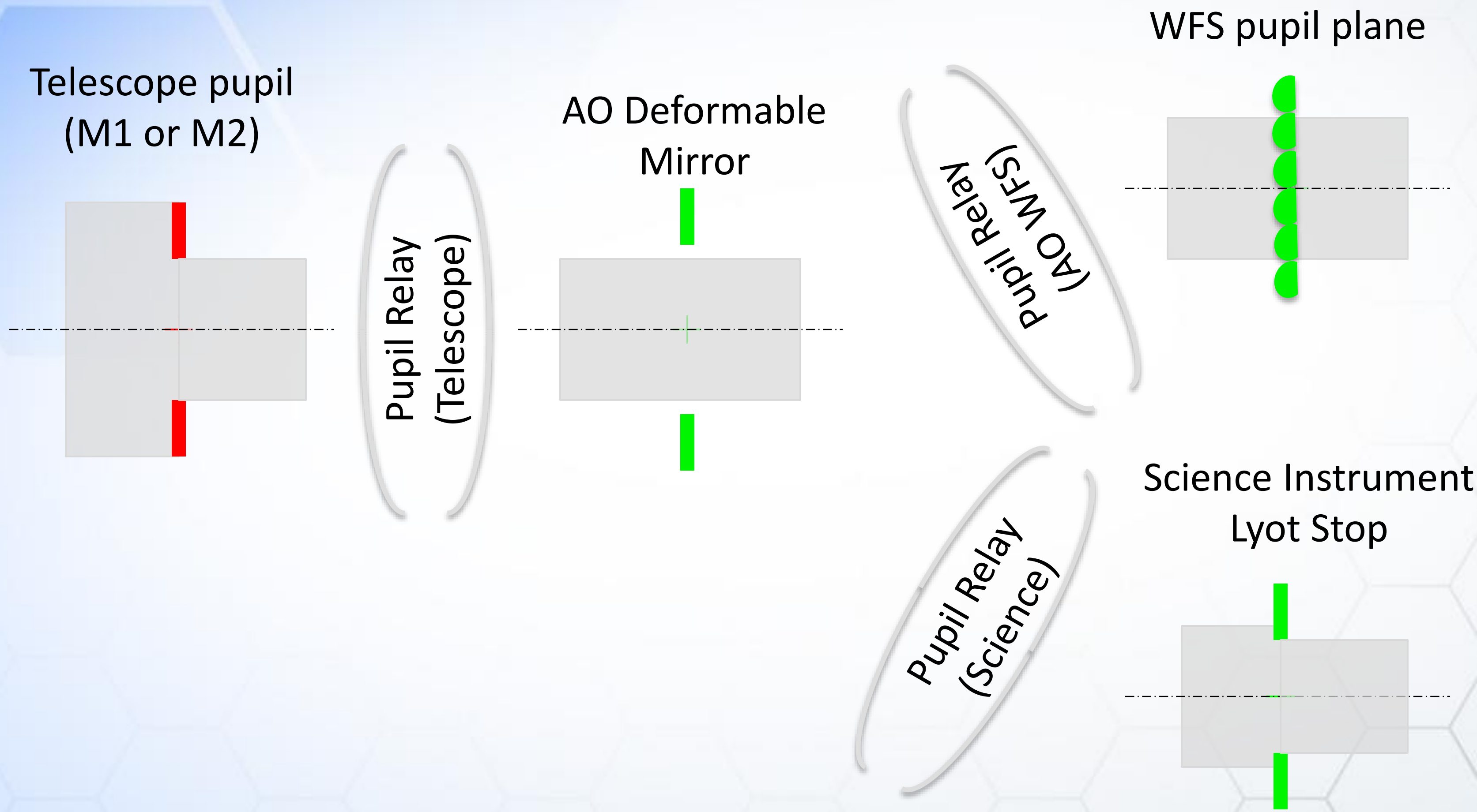
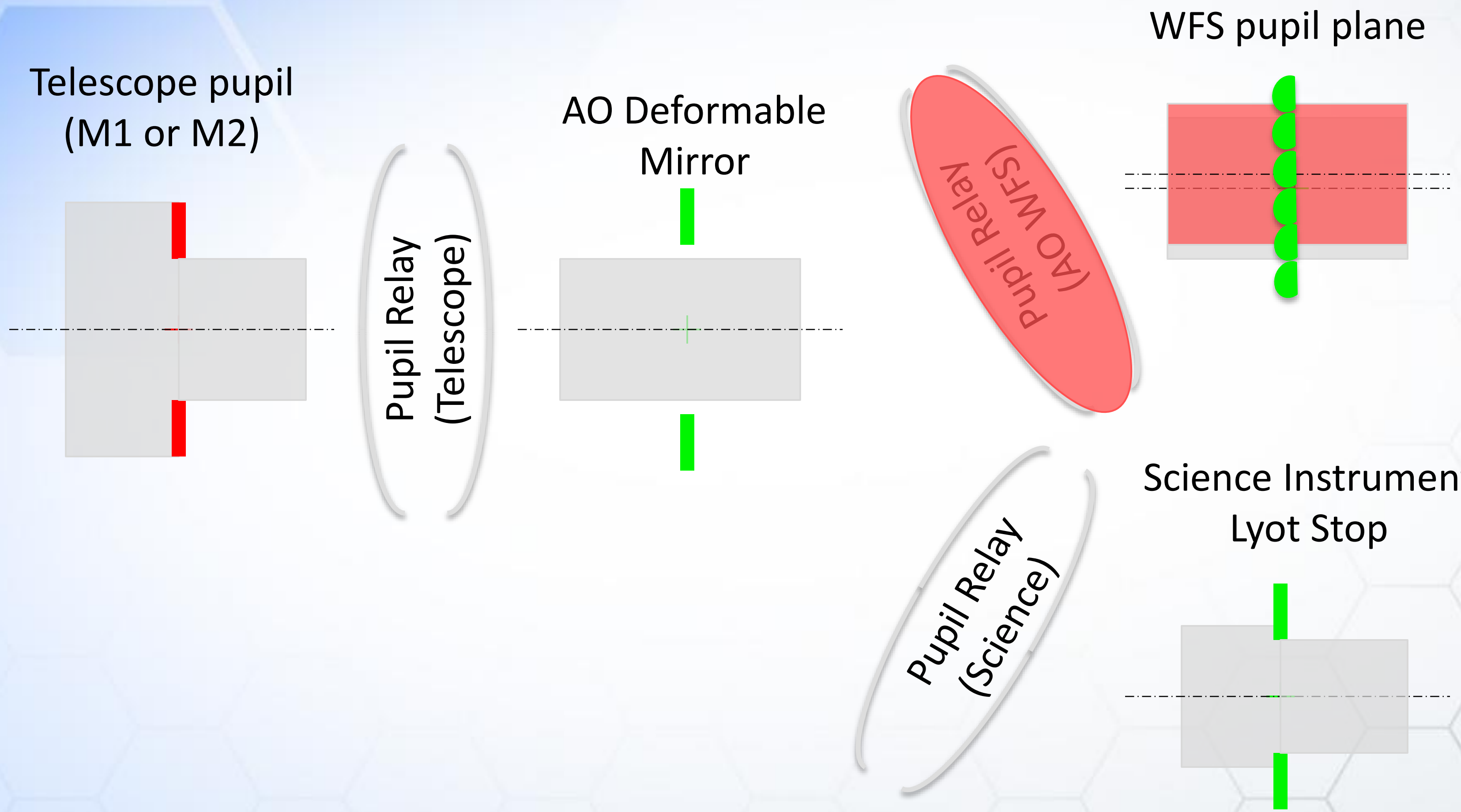
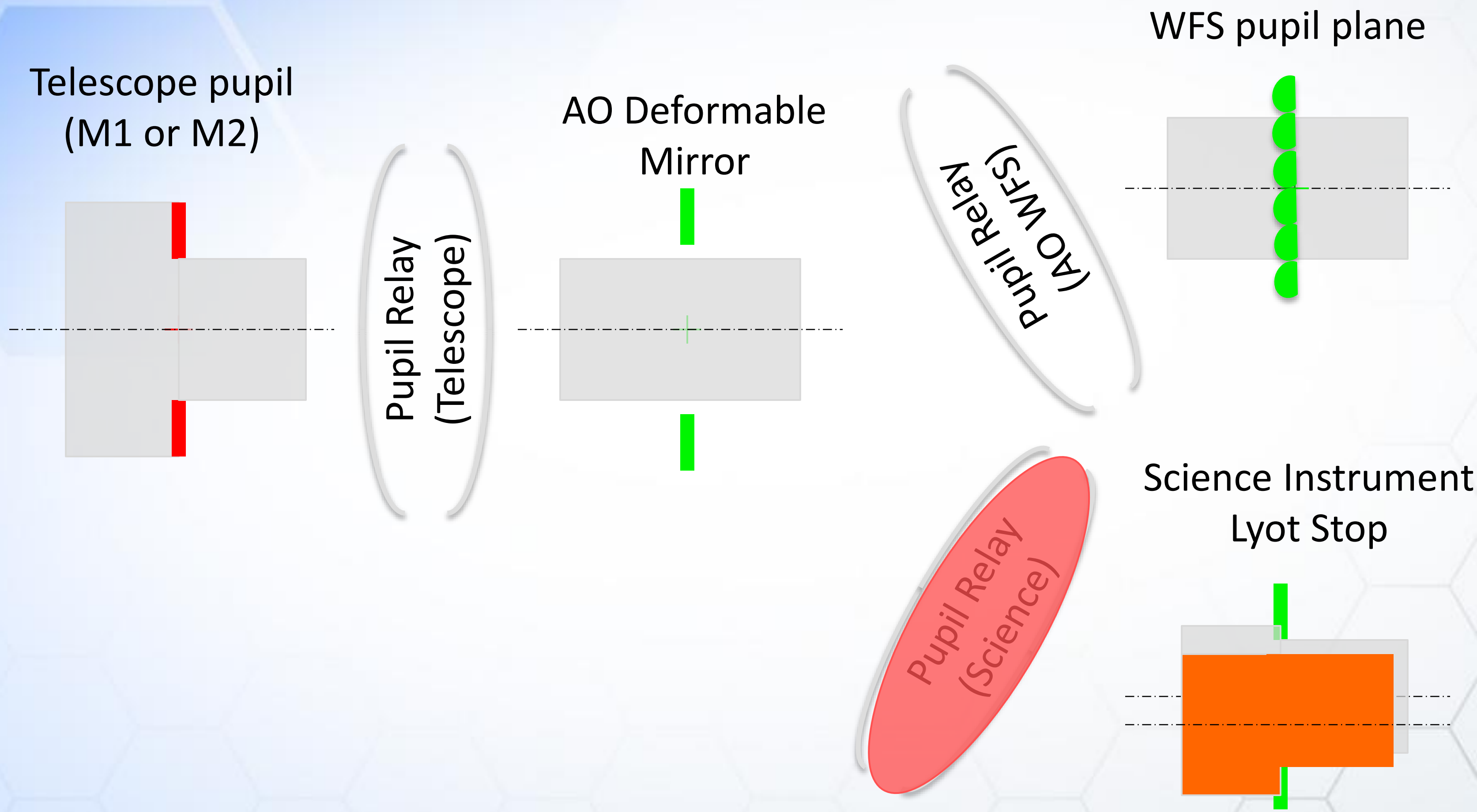
Pupil planes and pupil relays



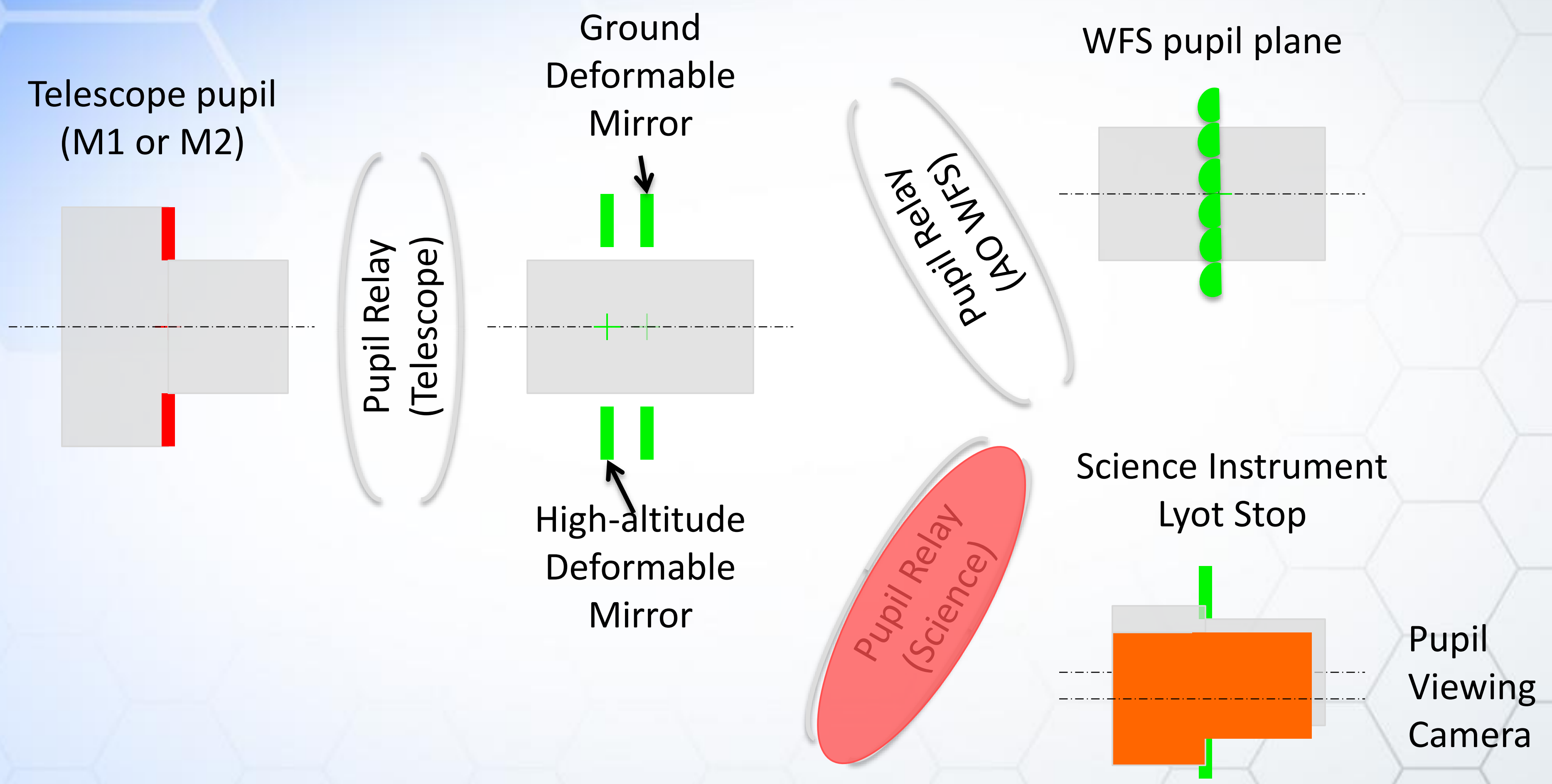
DM / WFS mis-registration



DM / Lyot stop mis-registration



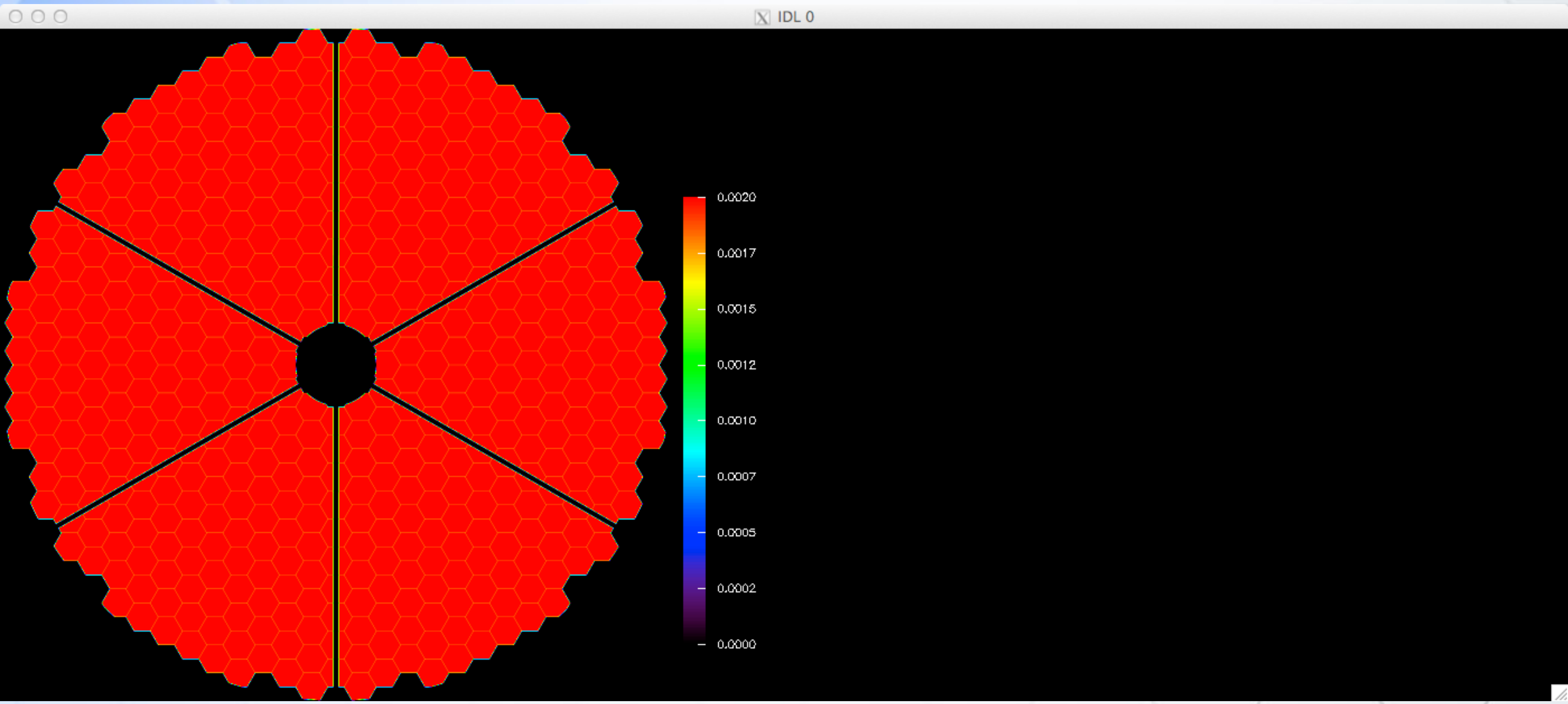
DM / Lyot stop mis-registration



Wave-front @ M1 (D=30m)

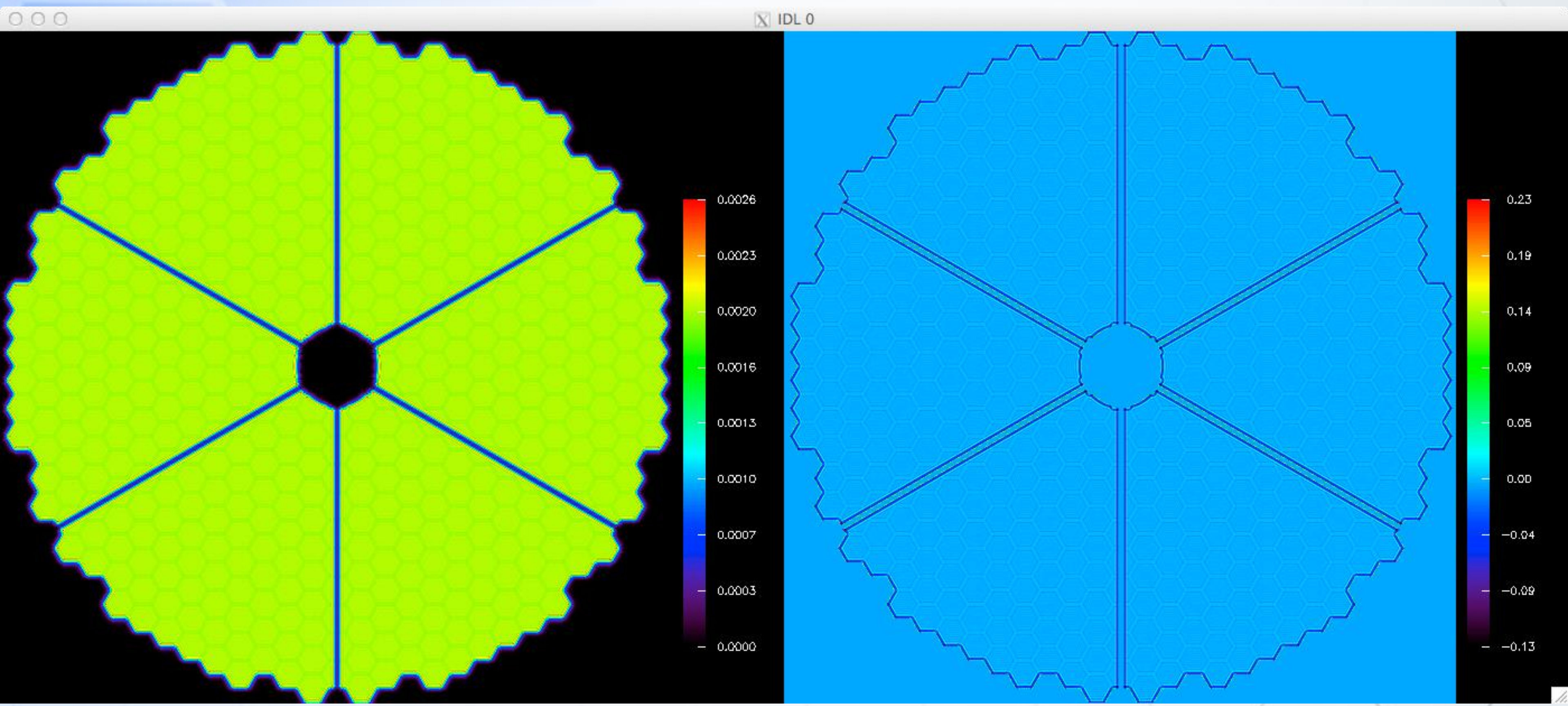
Amplitude

Phase



Wavefront @ DM11

Amplitude Phase



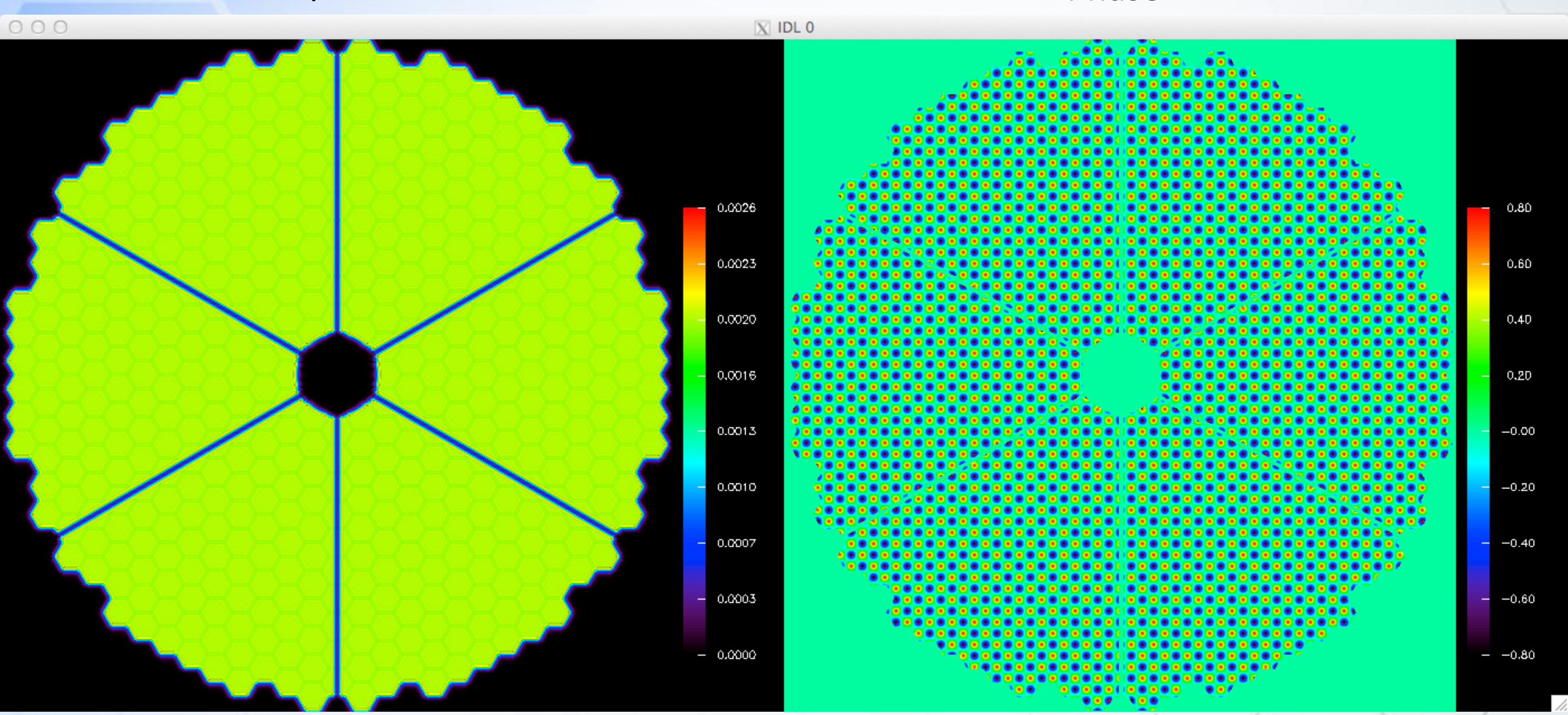
After propagation, the high spatial frequencies of amplitude have turned into phase

Wavefront @ DM11 after adding 1.5um P-V waffle on DM11

Thirty Meter Telescope

Amplitude

Phase

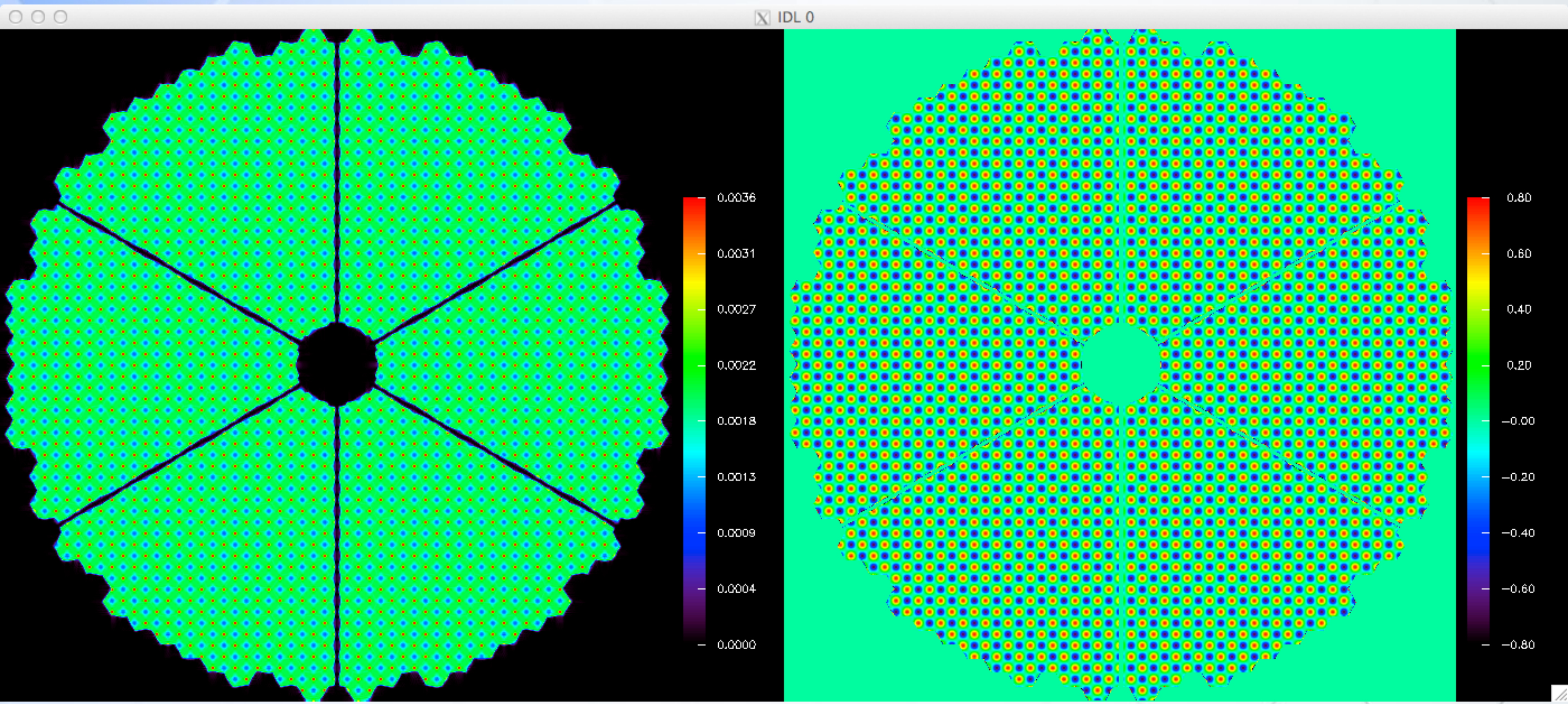


Amplitude does not change

Waffle added to phase

Wavefront propagated back to pupil (-11.8km propagation)

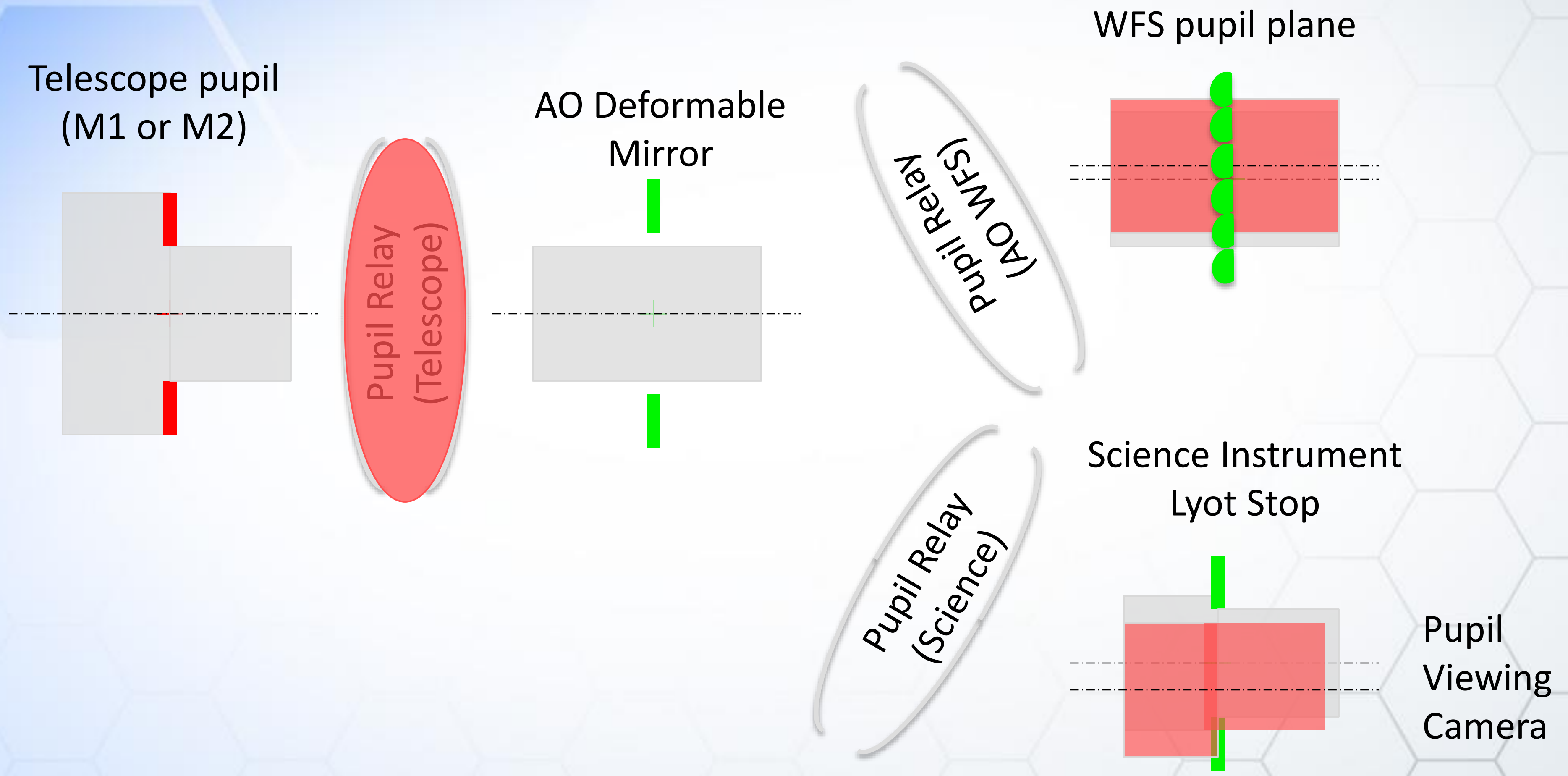
Amplitude | Phase



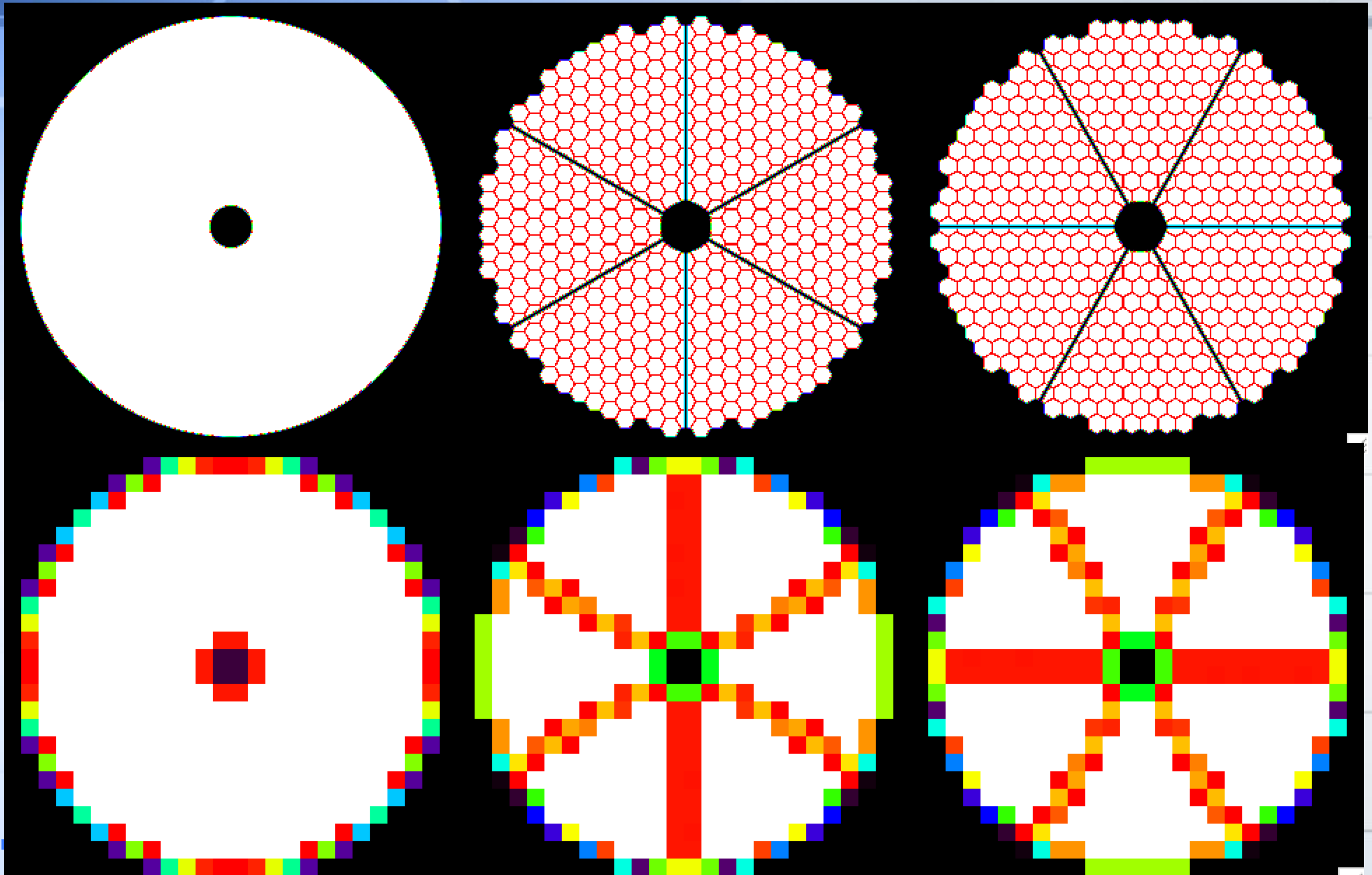
High spatial frequencies of waffle pattern have propagated to amplitude

Phase still largely contains waffle, with slightly increased amplitude

Telescope / WFS / Lyot mis-registration



TMT Pupils: full resolution and 24x24 binning

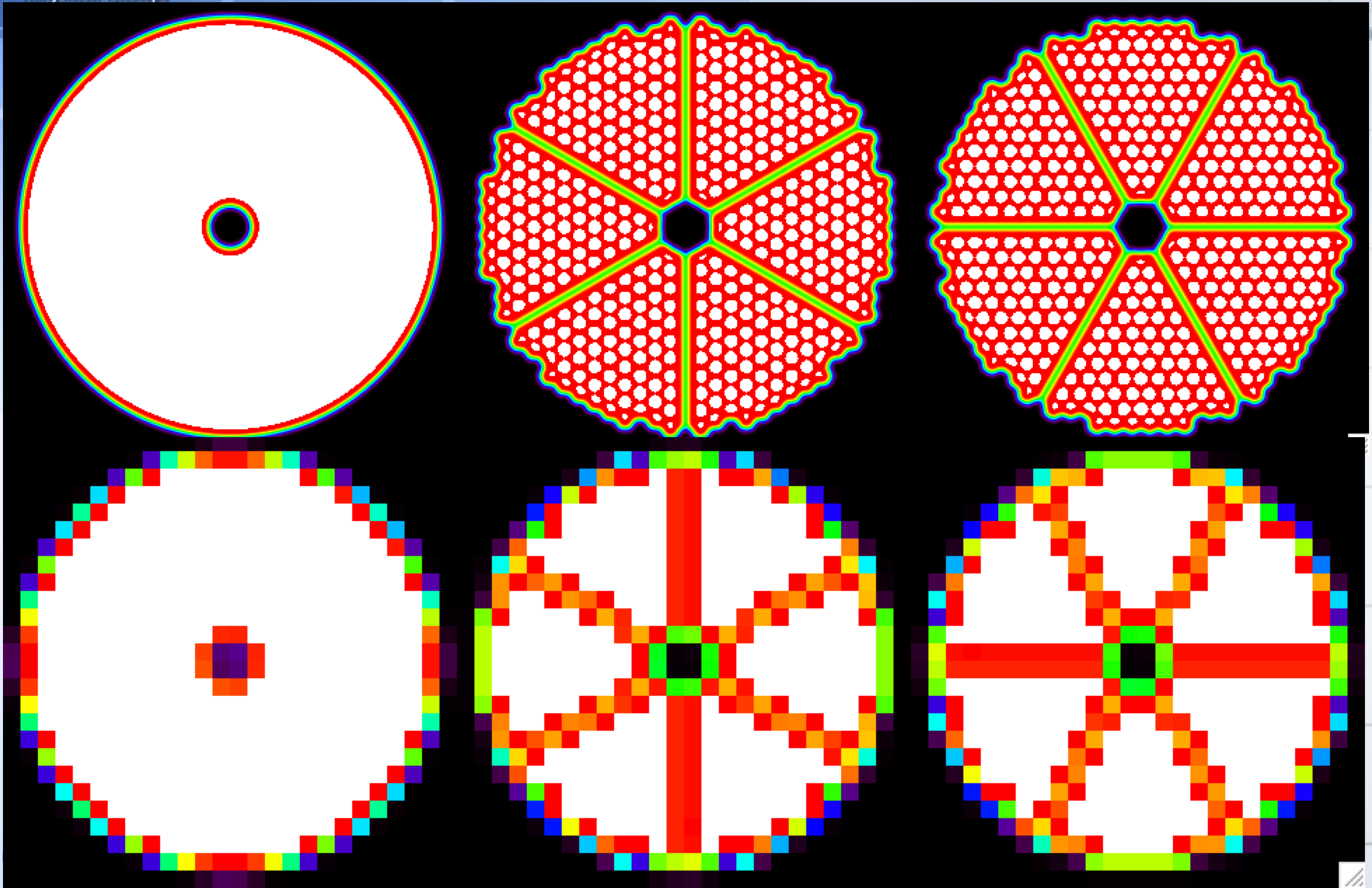


TMT Thirty Meter Telescope

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

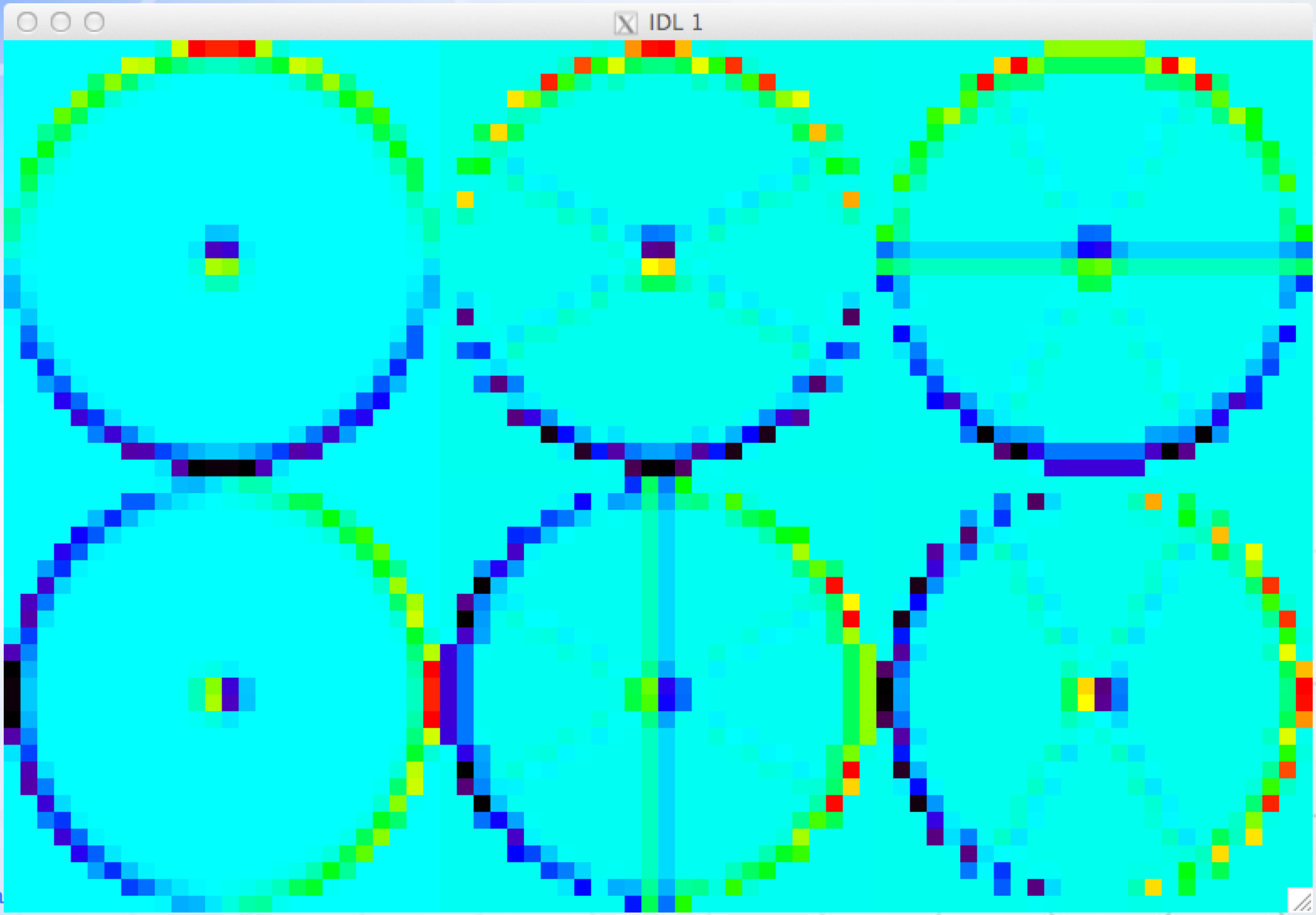
- zeroPointR=**1.35e10 ; photons/m^2/s**
- area=**15.^2*!PI ; TMT collecting area**
- tp=**0.424 ; throughput to WFS (QE=94%)**
- back = **660e3 ; photons/s/arcsec^2 (bright time)**
- back = **66e3 ; photons/s/arcsec^2 (dark time)**
- back = back * **1 * !PI^2 ; Through 2" field stop**
- rn = 1 electron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

- Segment reflectivity non-uniformity:
  - ±3% throughput for each segment **(Larry Stepp)**

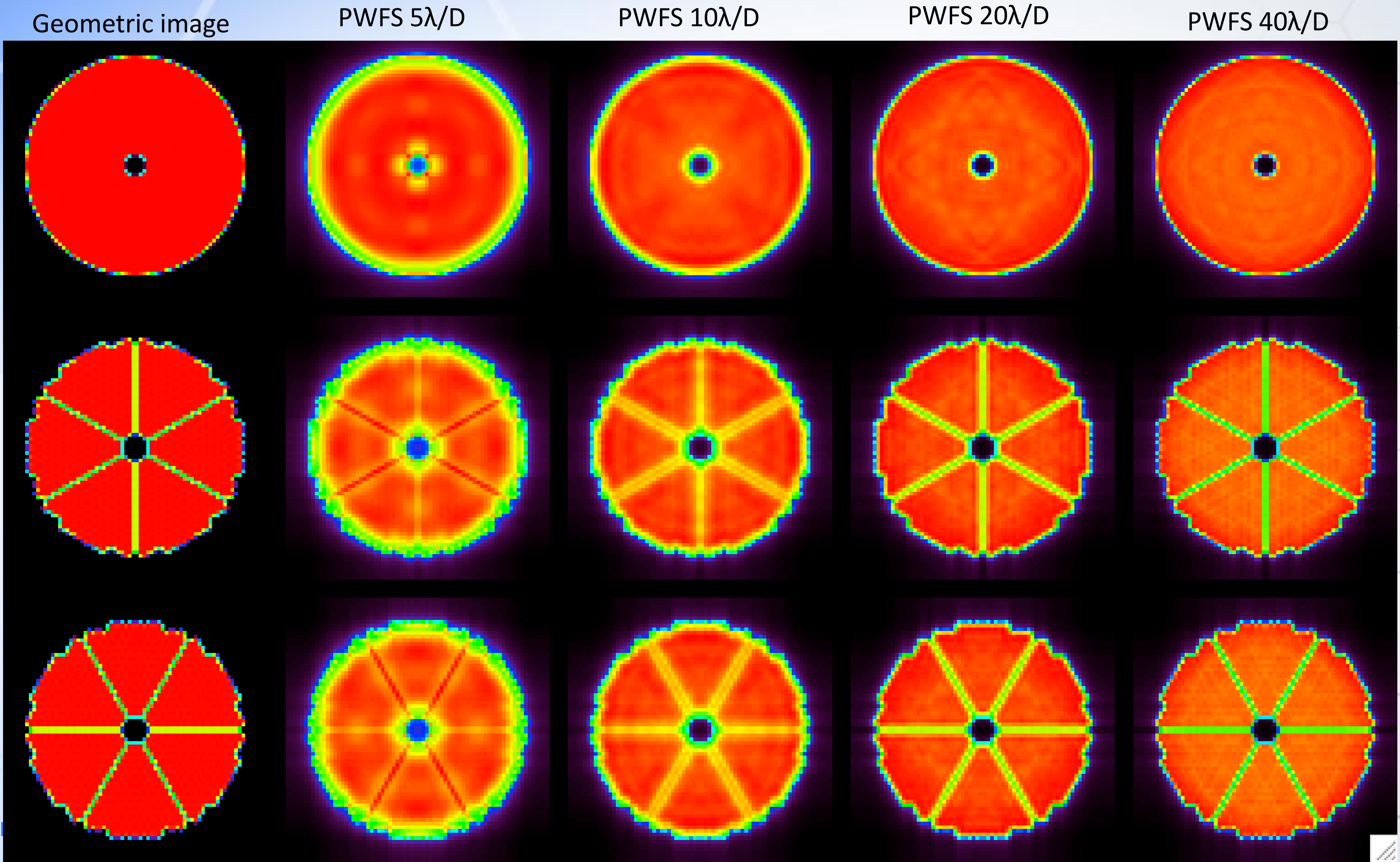
Pupil position estimation algorithms

- Pupil position is estimated from pupil image obtained from PWFS.
- Assumed magnitude: mR=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

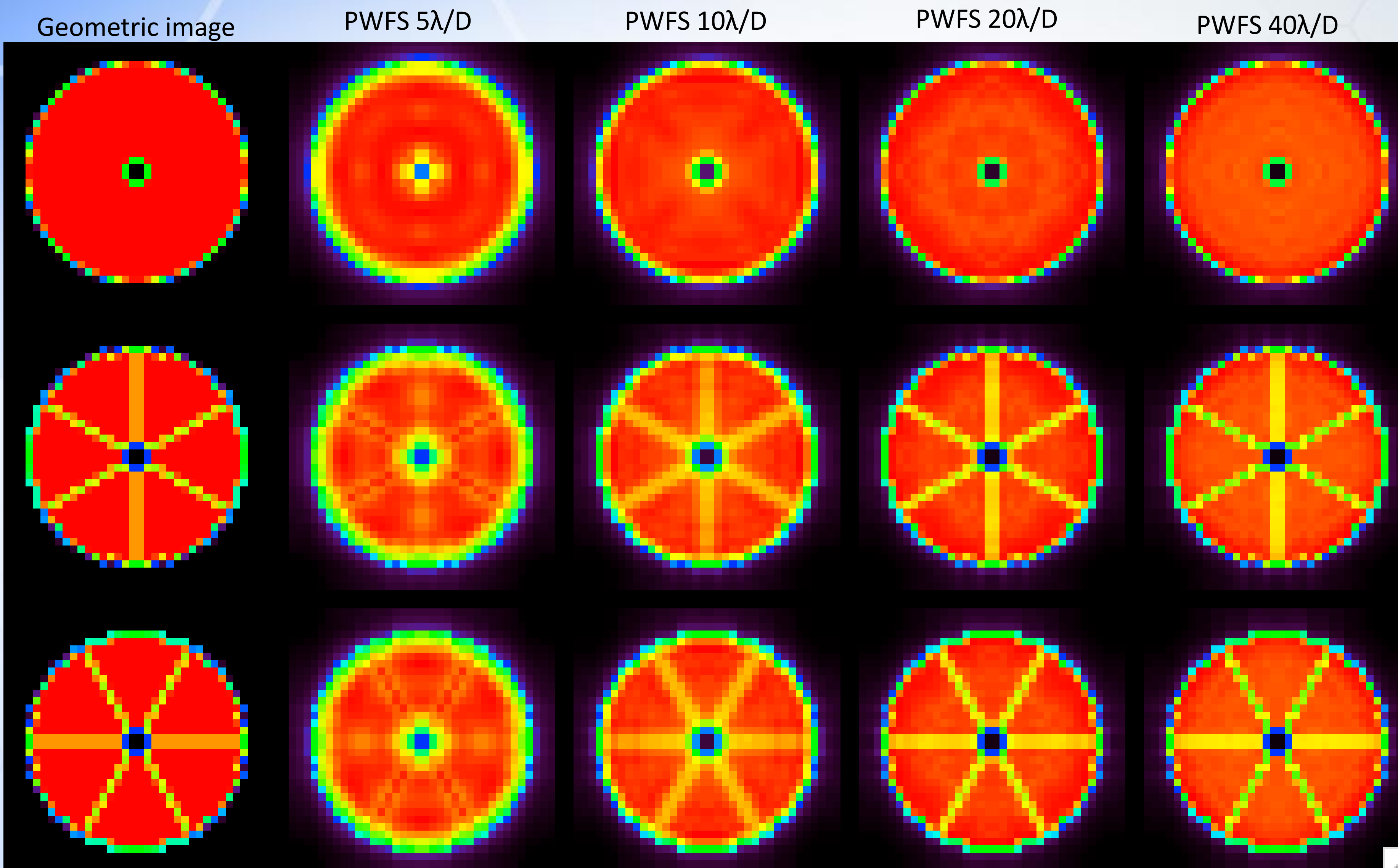
Matched filters



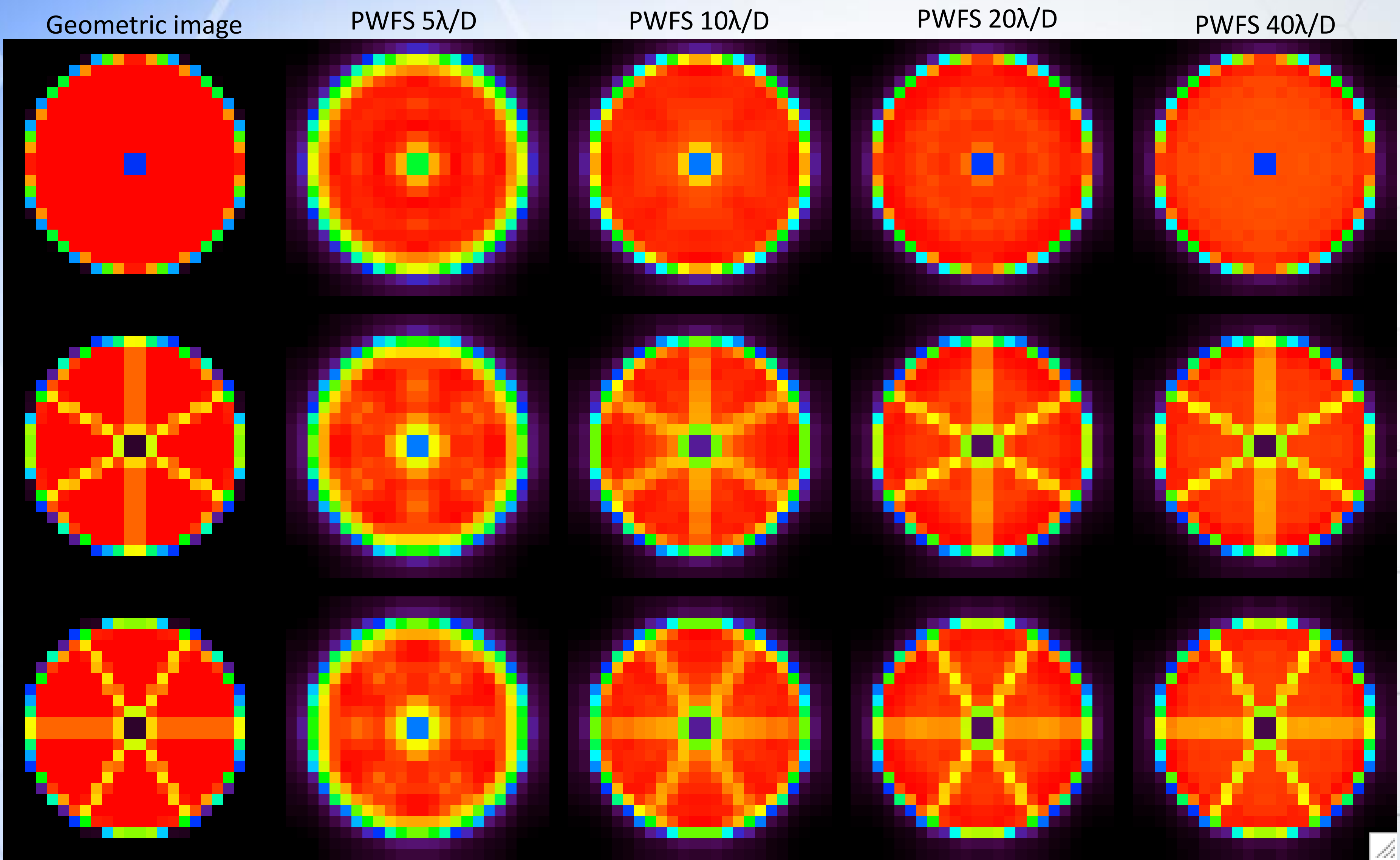
Pupil image at the PWFS 60x60 pixel resolution



Pupil image at the PWFS 30x30 pixel resolution



Pupil image of star at the PWFS 20x20 pixel resolution



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

	Circular pupil		TMT Pupil 1		TMT Pupil 2	
	RMS-x	RMS-y	RMS-x	RMS-y	RMS-x	RMS-y
Centroid	0.0260%	0.0259%	0.0255%	0.0257%	0.0256%	0.0256%
Correlation	0.0260%	0.0259%	0.0255%	0.0257%	0.0256%	0.0256%
Matched filter	0.0089%	0.0089%	0.0088%	0.0083%	0.0083%	0.0088%

RMS error with matched filter~ 0.01 %

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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

	Circular pupil		TMT Pupil 1		TMT Pupil 2	
	RMS-x	RMS-y	RMS-x	RMS-y	RMS-x	RMS-y
Centroid	0.0202%	0.0198%	0.0204%	0.0199%	0.0204%	0.0199%
Correlation	0.0202%	0.0198%	0.0204%	0.0199%	0.0204%	0.0199%
Matched filter	0.0043%	0.0043%	0.0048%	0.0041%	0.0041%	0.0046%

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

	Circular pupil		TMT Pupil 1		TMT Pupil 2	
	RMS-x	RMS-y	RMS-x	RMS-y	RMS-x	RMS-y
Centroid	0.0669%	0.0668%	0.0654%	0.0661%	0.0659%	0.0653%
Correlation	0.0669%	0.0668%	0.0654%	0.0661%	0.0659%	0.0653%
Matched filter	0.0221%	0.0218%	0.0216%	0.0205%	0.0208%	0.0216%

RMS error with matched filter~ 0.022 %

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

	Circular pupil		TMT Pupil 1		TMT Pupil 2	
	RMS-x	RMS-y	RMS-x	RMS-y	RMS-x	RMS-y
Centroid	0.0202%	0.0198%	0.0204%	0.0199%	0.0204%	0.0199%
Correlation	0.0202%	0.0198%	0.0204%	0.0199%	0.0204%	0.0199%
Matched filter	0.0040%	0.0040%	0.0045%	0.0038%	0.0039%	0.0044%

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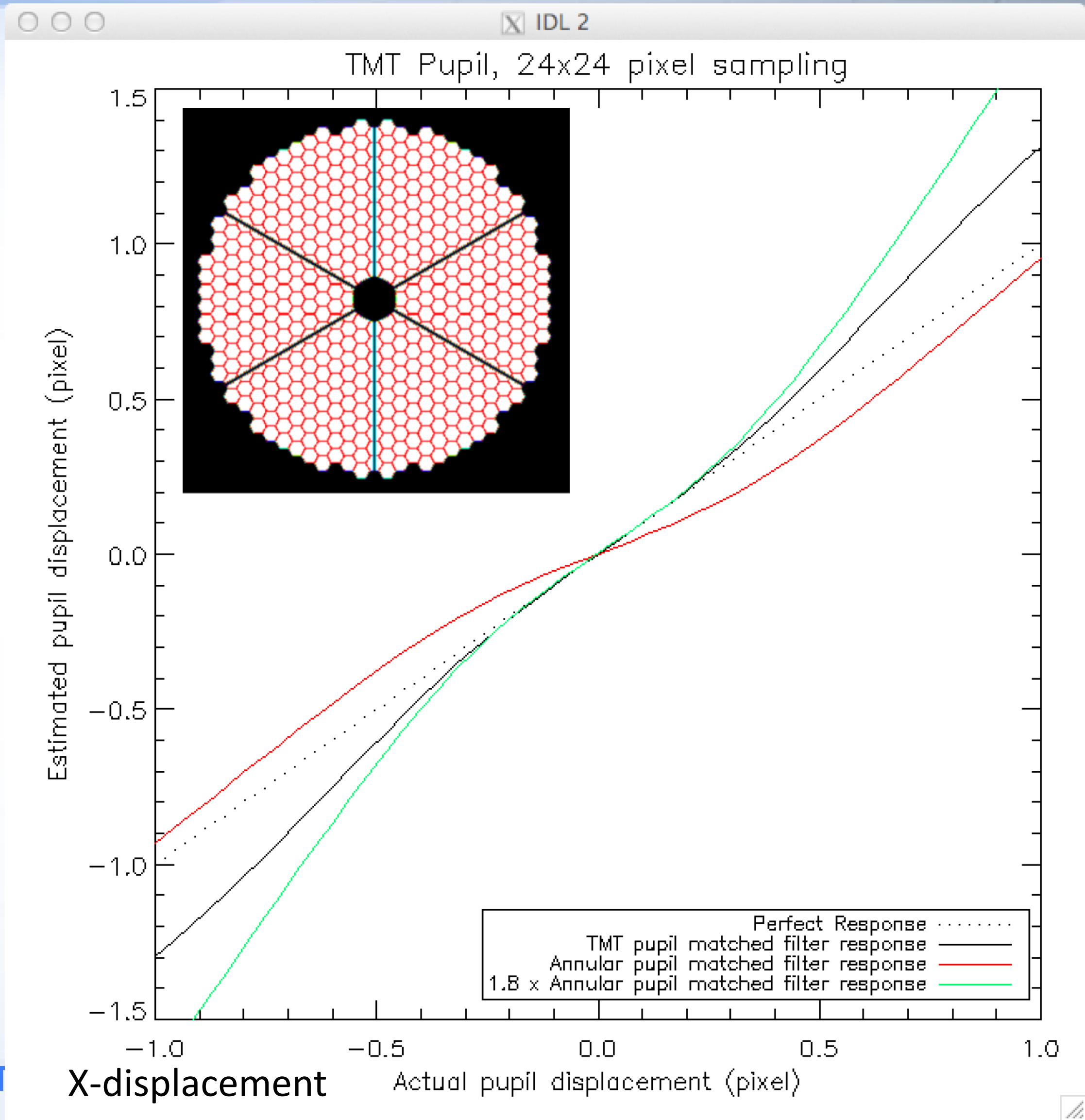
RMS error with matched filter~ 0.005% (same as bright time)

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



X-displacement

Dark time results
Annular pupil matched filter

Photon + read-out noise but no segment throughput fluctuations

	Circular pupil		TMT Pupil 1		TMT Pupil 2	
	RMS-x	RMS-y	RMS-x	RMS-y	RMS-x	RMS-y
Centroid	0.0669%	0.0668%	0.0654%	0.0661%	0.0659%	0.0653%
Correlation	0.0669%	0.0668%	0.0654%	0.0661%	0.0659%	0.0653%
Matched filter	0.0221%	0.0218%	0.0247%	0.0275%	0.0277%	0.0248%

RMS error with matched filter~ 0.028 %

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

	Circular pupil		TMT Pupil 1		TMT Pupil 2	
	RMS-x	RMS-y	RMS-x	RMS-y	RMS-x	RMS-y
Centroid	0.0202%	0.0198%	0.0204%	0.0199%	0.0204%	0.0199%
Correlation	0.0202%	0.0198%	0.0204%	0.0199%	0.0204%	0.0199%
Matched filter	0.0037%	0.0036%	0.0040%	0.0040%	0.0040%	0.0039%

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