Decreasing the inner working angle in high-contrast imaging by pupil replication

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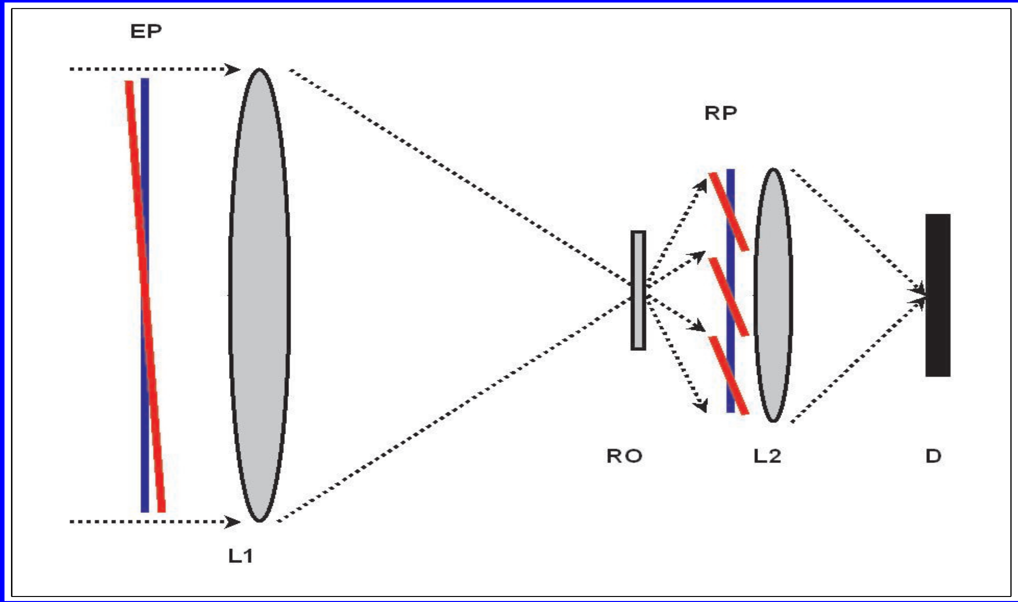
(presenting)

Pupil replication is …

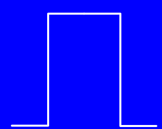
- additional to high contrast imaging systems
- between telescope and high contrast system
- before the wavefront correction and mask
- Principle:



Equations: 1 dimension

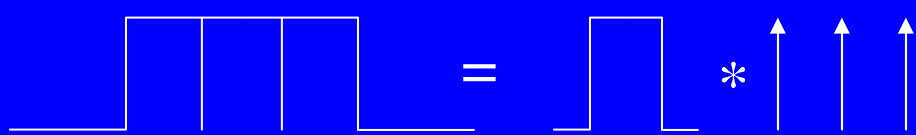
in 1 dimension, plane wave on axis, hard edged pupil:

wave + pupil: imaged:



FT

sin(x)/x = sinc(x)



FT

sinc(x) (1+2cos(x))

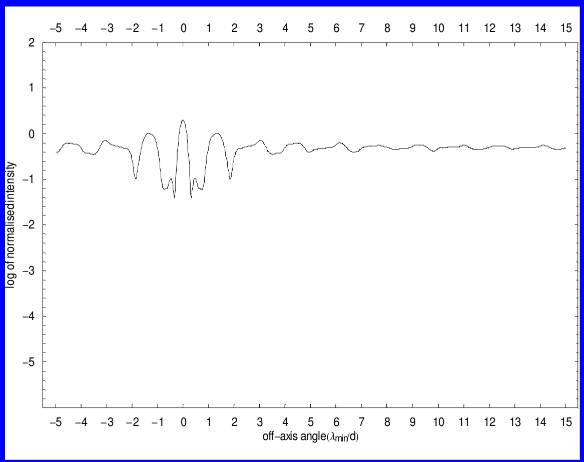
$$T = A\left(1+2\cos\left(2d\pi x/\lambda\right)\right)\operatorname{sinc}\left(d\pi\left(x-\sin\left(\alpha\right)\right)/\lambda\right)$$

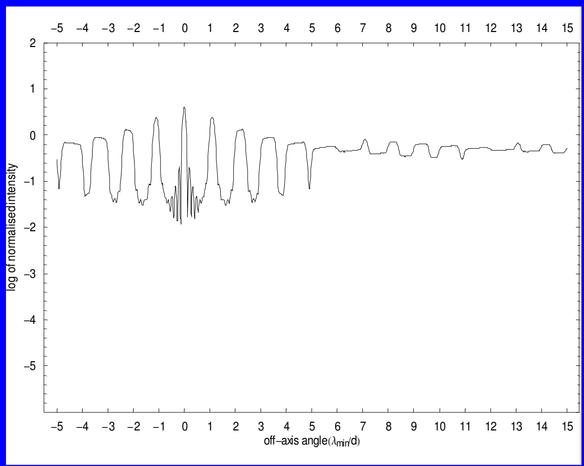
=> cosine not dependent on α

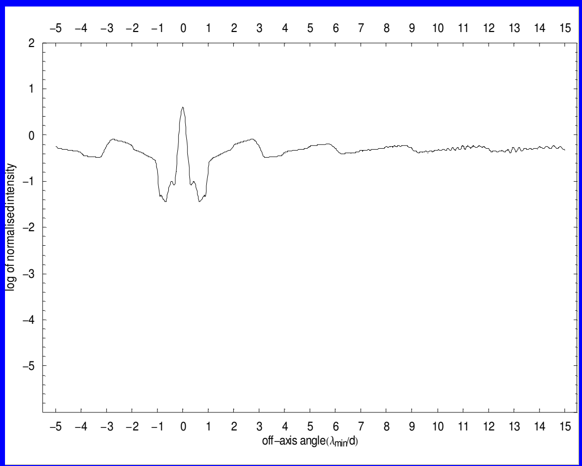
Cosine

$$T = A\left(1+2\cos\left(2d\pi x/\lambda\right)\right)\mathrm{sinc}\left(d\pi\left(x-\sin\left(\alpha\right)\right)/\lambda\right)$$

- PSF = 'Airy'-pattern x cosine^2
- N replications => N/2 cosines
- Different frequencies: both *d's* and λ's
- Figures: log of cosine^2 in broadband (100 steps)
  4x 500-800nm / 8x 500-600nm / 8x 6-18μm



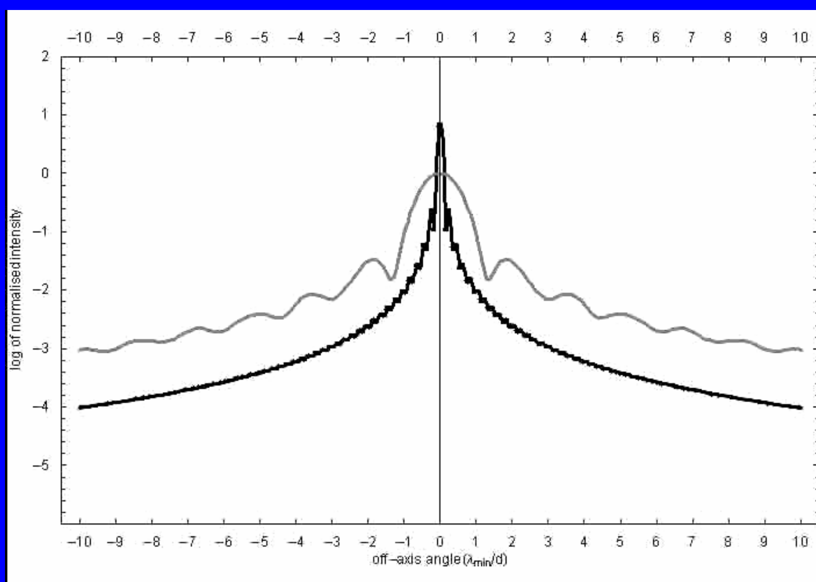




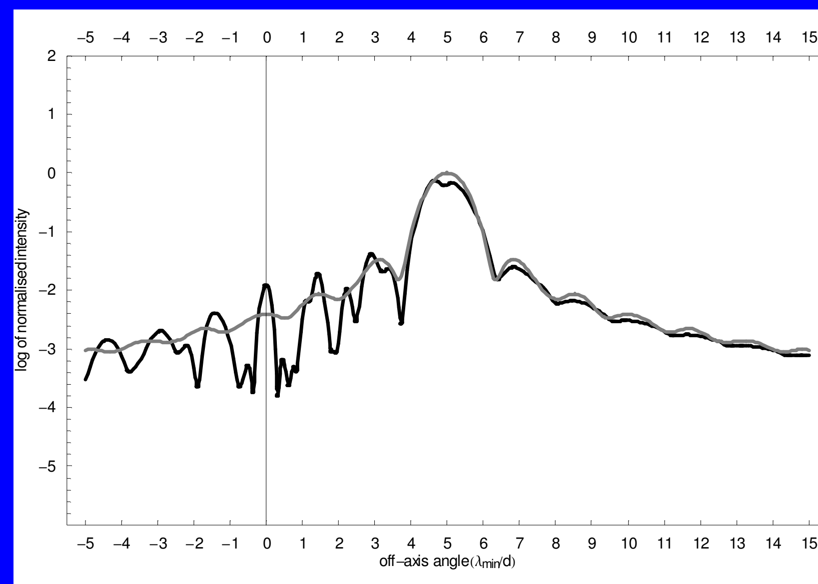
Off axis (planet) PSF

- 8 replications, 500-800nm in 100 steps:

on axis

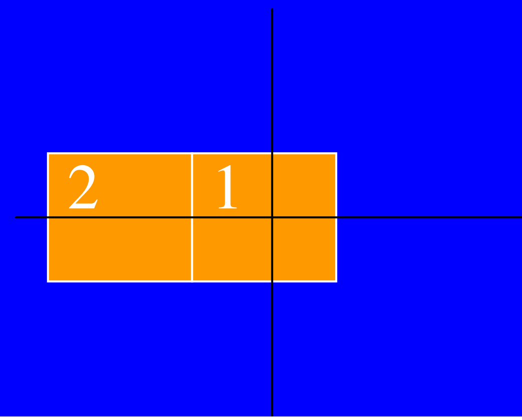


5 λ/D (λ=500)



Equations: 2-D with errors

- Two dimensions, square aperture
- 2x replication
- Optics with errors (on ‘2’)



$$T = T_{x1}T_{y1} + T_{x2}T_{y2}$$

$$T_{x2} = A_2 e^{i2\pi\left(p + \left(x/\lambda\right)(d+s)\right)} \operatorname{sinc}\left(d\pi\left(\left(x - \sin(\alpha)\right)/\lambda - f\right)\right)$$

$$T_{y2} = A_2 e^{i2\pi\left(p + \left(y/\lambda\right)(h)\right)} \operatorname{sinc}\left(d\pi\left(\left(y - \sin(\alpha)\right)/\lambda - g\right)\right)$$

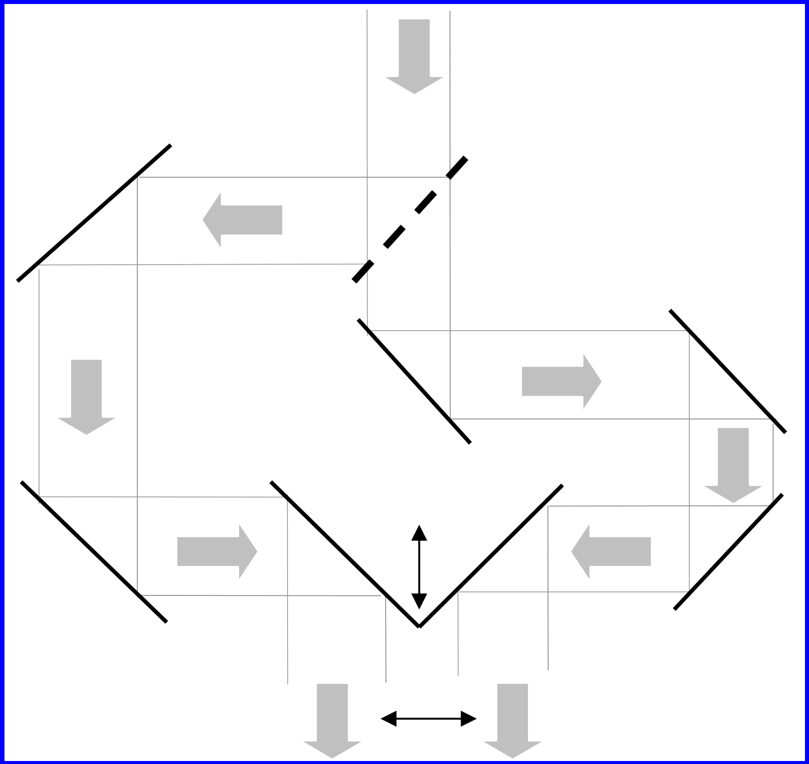
- => requirements same as for telescope

Nota bene

- No ‘flux dilution’ in analysis or simulations (…)
- Does not work like a hypertelescope (…)
- Does not work like a blazed grating
- Optics requirements same as for telescope
- Replication before wavefront correction
- Beyond diffraction limit (…)
- Principle has been proven experimentally (…)
- Replication optics =>

Replication optics

- 2-fold replication unit, 1 beamsplitter and 7 mirrors
- 4 reflections in each arm
- Equal optical path length
- Adjust last prism to correct pathlength and vary replica separation => shift error avoided
- Can be monolithic
- To be cascaded: 2^N

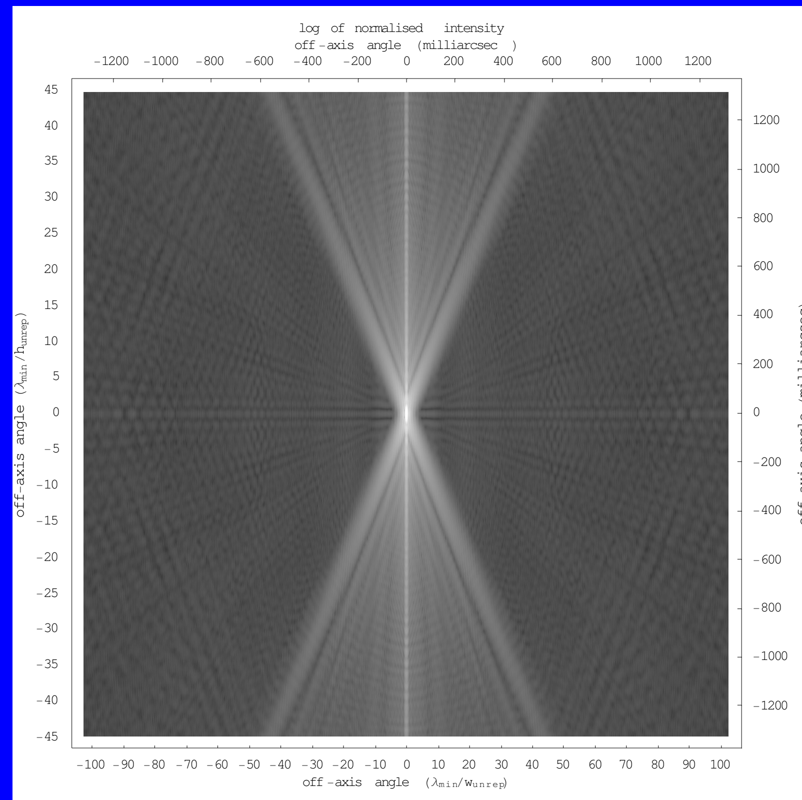


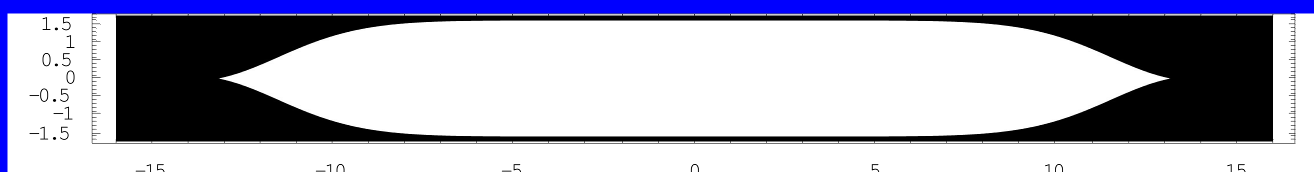
Project results

- Simulations and analyses
- Using square and hexagonal pupils
- Applied to Lyot coronagraphy
- Applied to pupil apodisattion
- Included obscuration (=> no improvement)
- Applied to nulling (=> no improvement)
- Shaped pupil mask: TPF-like case
- => good and bad news

Field (simulation)

- Pupil: 8x3.5m
- 4x replication in long direction
- 500-800 nm
- Super Gaussian mask ($\exp(-x^8)$)





Cross-section (analysis)

- Analysis, amplitude *R* of a 2x replicated system with a Gaussian mask (=> proceedings):

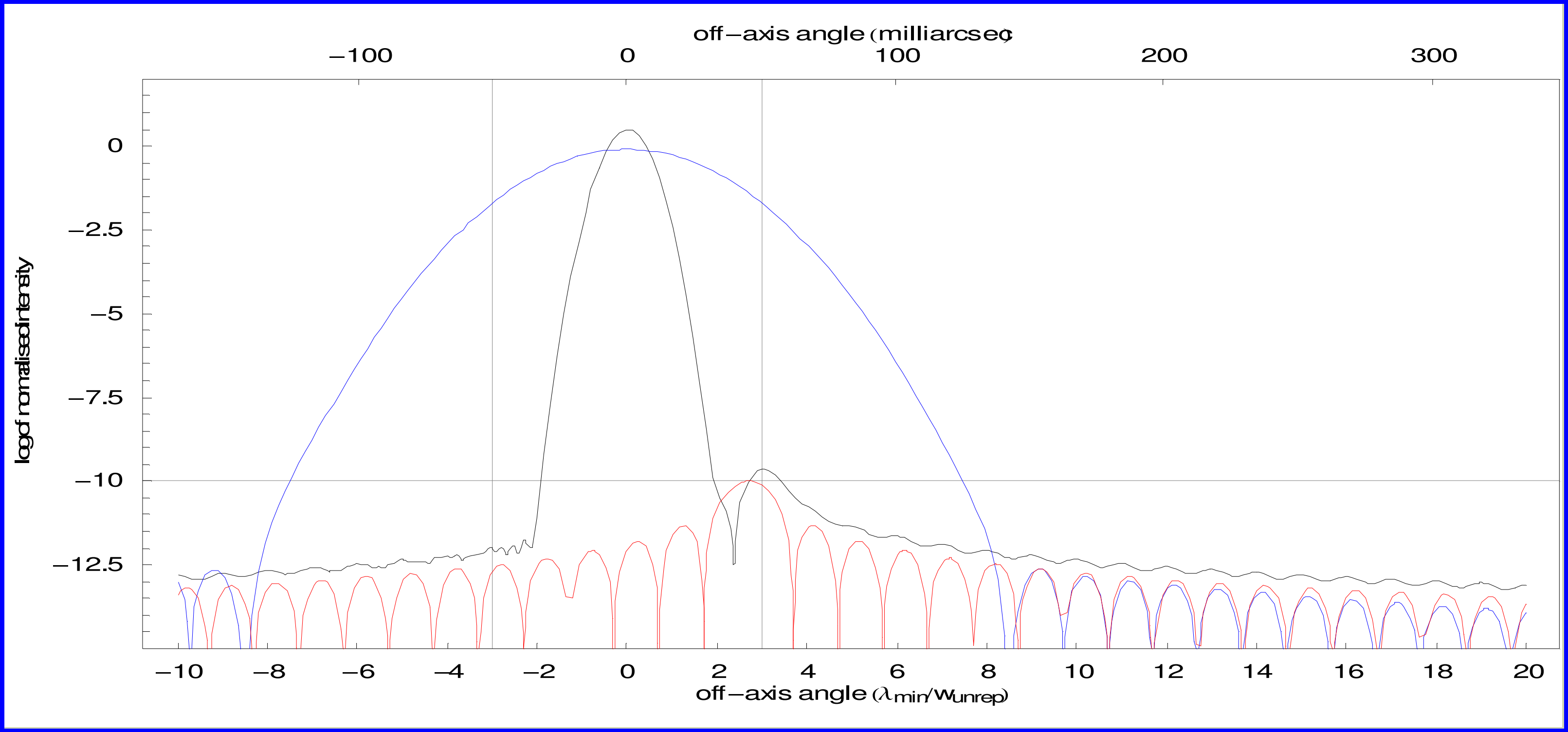
$$R = R_1 + R_2^+ \left(R_3^+ - R_4\right) + R_2^- \left(R_3^+ + R_4\right)$$

$$R_1 = 4Ac_1 w \cos\left(\pi w \xi / \lambda\right) \operatorname{sinc}\left(\pi w\left(\xi - \alpha\cos(\beta)\right) / \lambda\right) \qquad R_2^{\pm} = \frac{Ac_2}{\sqrt{c_3}} \sqrt{\pi} e^{-\left(\left(\pi\left(\xi - \alpha\cos(\beta)\right)\right)^2 \pm i\pi c_3 w \lambda \alpha \cos(\beta)\right) / c_3 \lambda^2}$$

$$R_3^{\pm} = erf\left(w\sqrt{c_3} \pm i\pi\left(\xi - \alpha\cos(\beta)\right) / \sqrt{c_3}\lambda\right) \qquad R_4 = erf\left(i\pi\left(\xi - \alpha\cos(\beta)\right) / \sqrt{c_3}\lambda\right)$$

Cross-section (analysis)

- Gaussian mask, λ=650 nm
- Planet at 10^{-10} and 2.7 λ/D (< 50 mas)



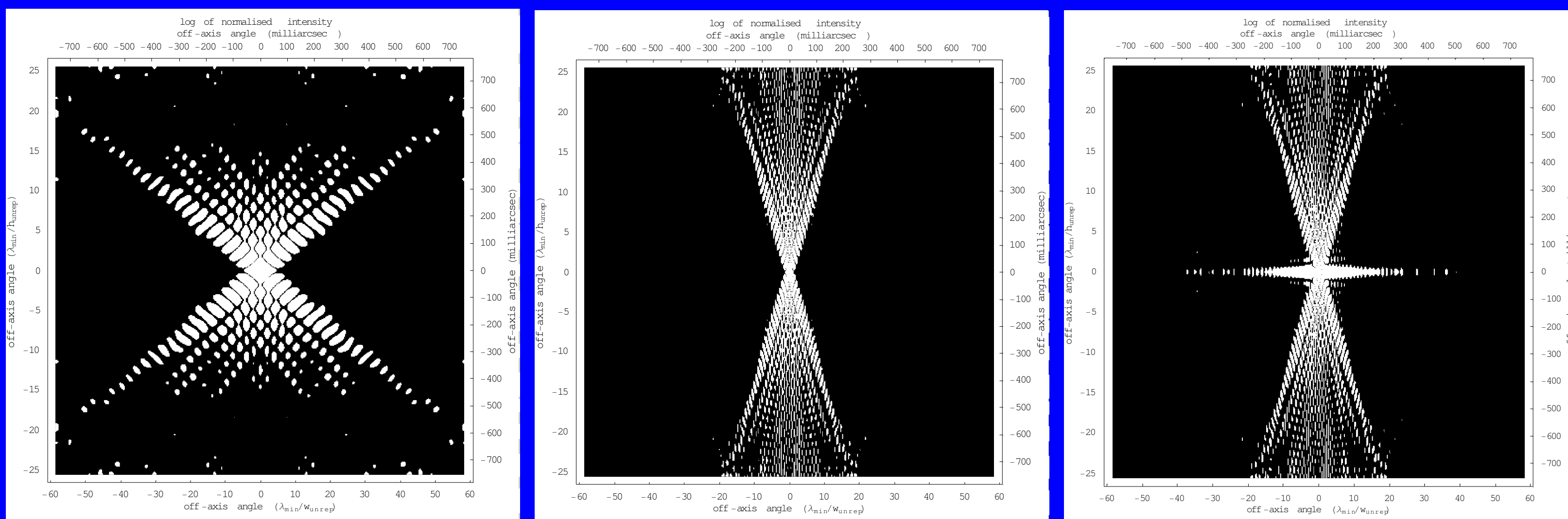
Performance

- Simulations and analysis mixed:
- Contrast: 10^{-10}
- Inner Working Angle: 30 mas
- Field Of View: ~70%
- Throughput (replication+mask-supergauss): 57%

- Problem: pointing error (off-axis star)

Pointing error

- Figures (thresholded):
  - unreplicated, replicated, idem with pointing error



  - Requirement for 10^{-10} contrast on *x*-axis:
    in replication direction: ~10^{-5} λ/D = O(μas)
    for rotation: 2 arcsec

Conclusion

- Future work:
  - Influence of wavefront correction
  - Breadboard

- Reference:
  - Astrophysical Journal Letters 618
    Pupil Replication for Exo-Planet Imaging
    Greenaway et al.
    10 January 2005

Discussion