Pupil Replication for exo-planet imaging

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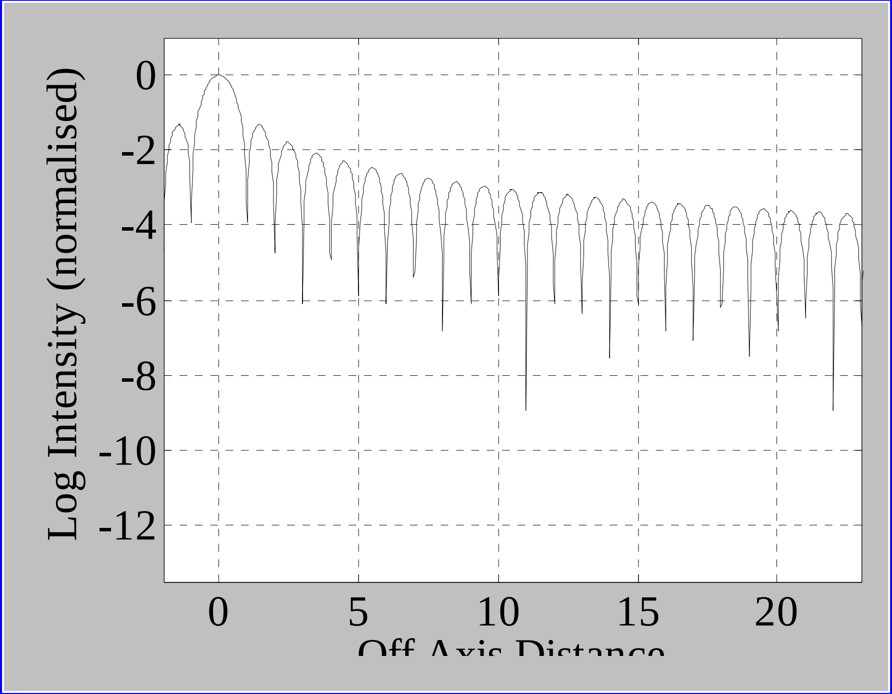
Overview

	Slides:
• Principle	(3)
• Analysis: 1-D, 2-D, errors	(4)
• Optics design	(1)
• Simulation of applications	(7)

Star flux problem

principle – analysis – optics - application

- Flux from host star dominates exoplanet
- Problems:
  - contrast
  - inner working angle
- Techniques to suppress scattered host flux:
  – coronography
  – pupil apodisation
  – Interferometry
- Pupil replication helps



diffraction limited PSF, x-axis in λ/d

Principle

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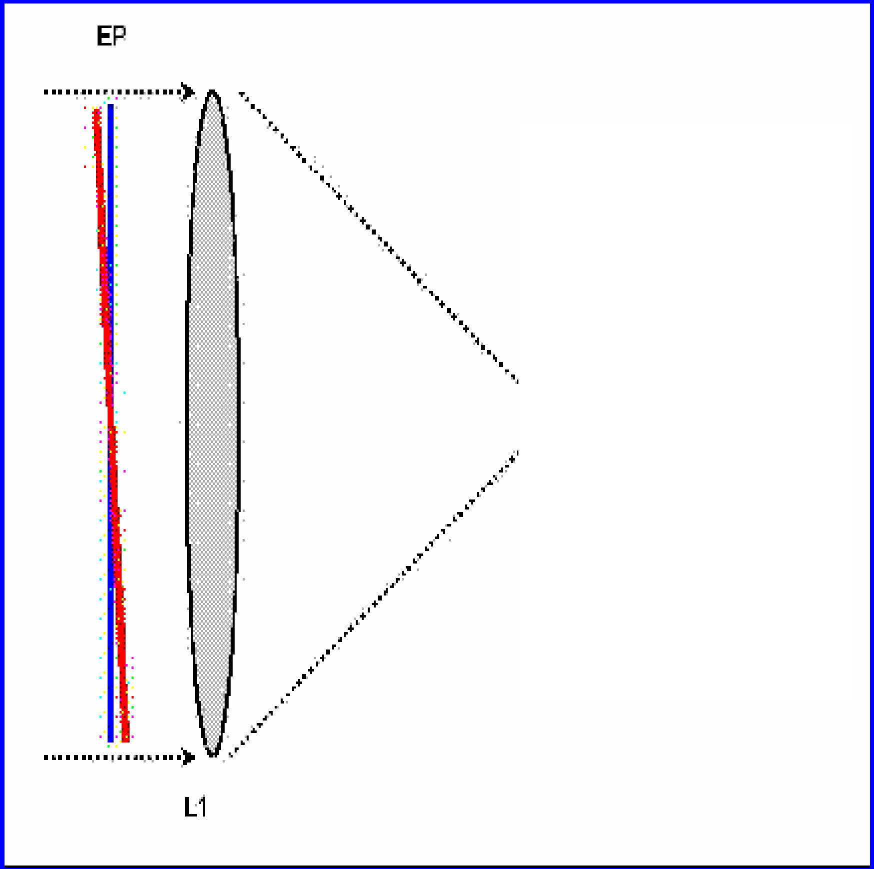
- Start with normal telescope
- Include replication optics and second imaging lens.
- Axial wavefront is continuous (blue), like larger telescope.
- Non-axial wavefront is discontinuous (red).



from ApJL 618

Expectations

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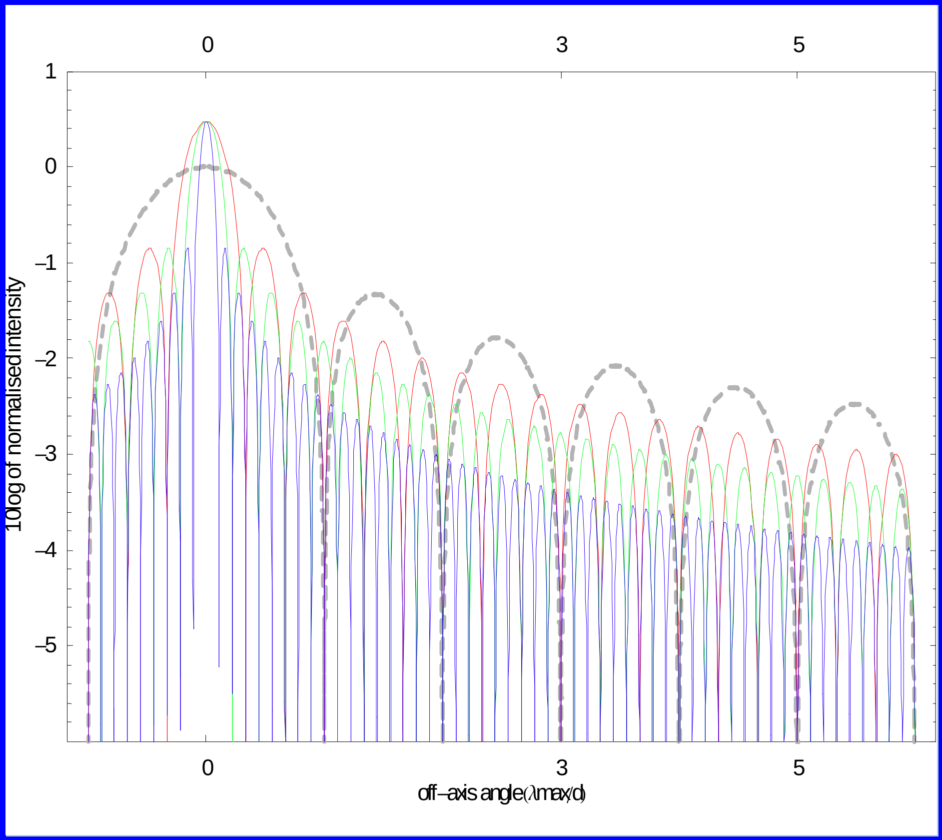
- Consider 3-fold replication in one dimension
- ***Axial*** pupil wavefront is 3x wider and 3x fainter
- ***Image*** of unresolved axial star is 3x ***narrower*** and 3x ***brighter***
- Sidelobes are 3x ***fainter***
- Image stop to remove star flux can be smaller
- ***Inner Working Angle can be improved***



Analysis (one dimension)

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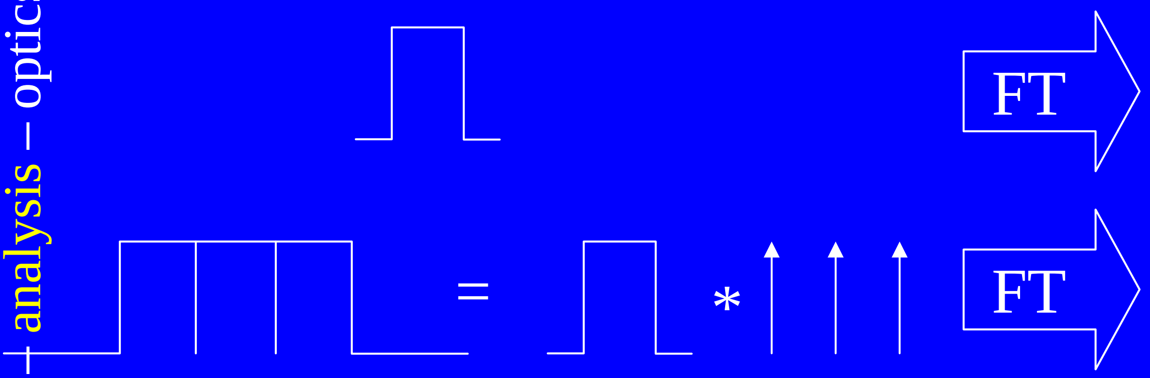
in 1 dimension, plane wave on axis, hard edged pupil:

wave + pupil: imaged:



$\sin(x)/x = \mathrm{sinc}(x)$

$\mathrm{sinc}(x)\ (1+2\cos(x))$

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

Two Dimensions

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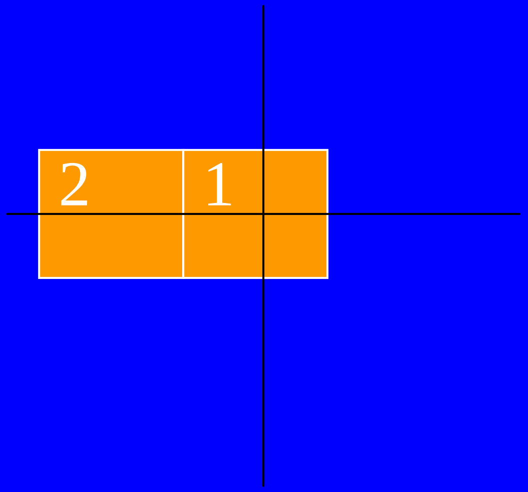
- Square pupil (seamless replication) then: 2-D amplitude T

$$T = T_x T_y$$

- T for two replications 1 and 2
  - 1 is on axis, 2 is adjacent



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

  - errors imposed on 2

Including Errors

- Pupil 1: T_{1x} and T_{1y} are sinc functions
- Pupil 2 has errors in x (and y) direction:
  - shift s, shear h, piston p, tilt f and tip g

$$T_{2x} = A_2 e^{i2\pi\left(p+\left(x/\lambda\right)(d+s)\right)} \operatorname{sinc}\left(d\pi\left(\left(x-\sin(\alpha)\right)/\lambda - f\right)\right)$$

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

Error Evaluation

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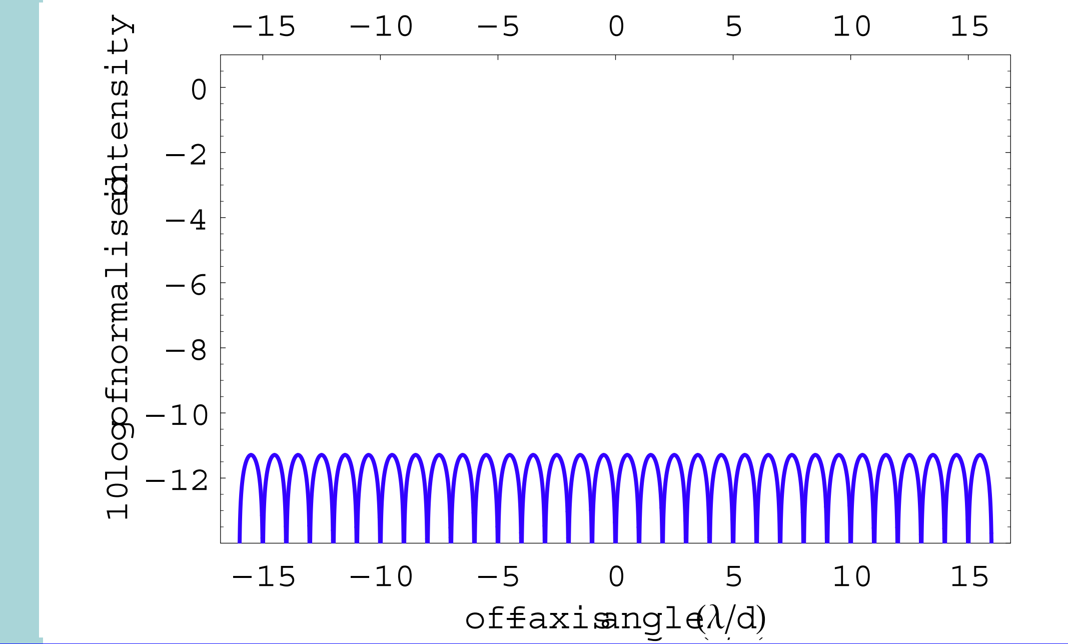
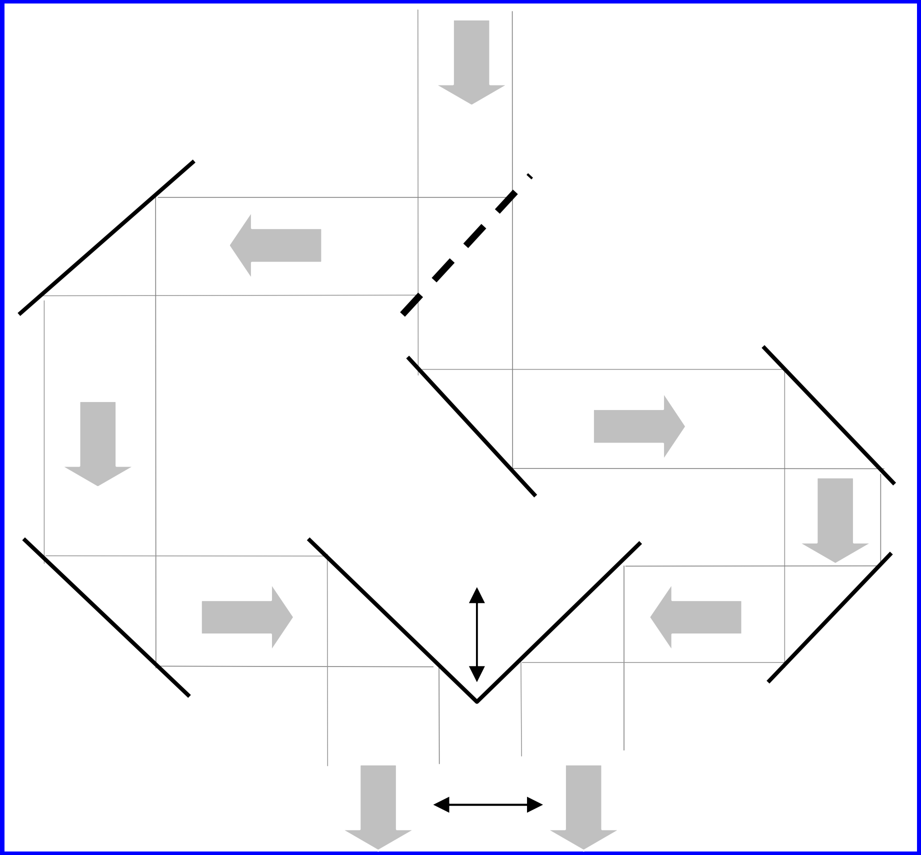
- 2-D analyses; horizontal crosssection
- If PSF(no error) - PSF(with error) < 10^{-10}
  - example: shift = d 10^{-3} (10^{-5}) => 100 (1) micron for 1 cm pupil
  - difference images =>
- Alternative method: PSF of (error – no error)



Replication Optics (2-fold)

- Use 1 beamsplitter and mirrors
- Equal:
  - # reflections in each arm
  - optical path length
- Adjust last prism to vary replica separation => shift error avoided
- Can be cascaded
- Can be monolithic



Application

- Pupil replication applied to pupil *apodised* coronagraph
- Used simple not optimised function for attenuation B:
  - Super Gaussian
  - x = off-axis angle
  - c is adjusted to attenuate by 10^{-4} at pupil edge (both un- and replicated)

$$B(x) = e^{-\left(x/c\right)^{8}}$$

- Expect to
  - broaden the image core
  - reduce side-lobes

principle – analysis – optics - application

Simulation

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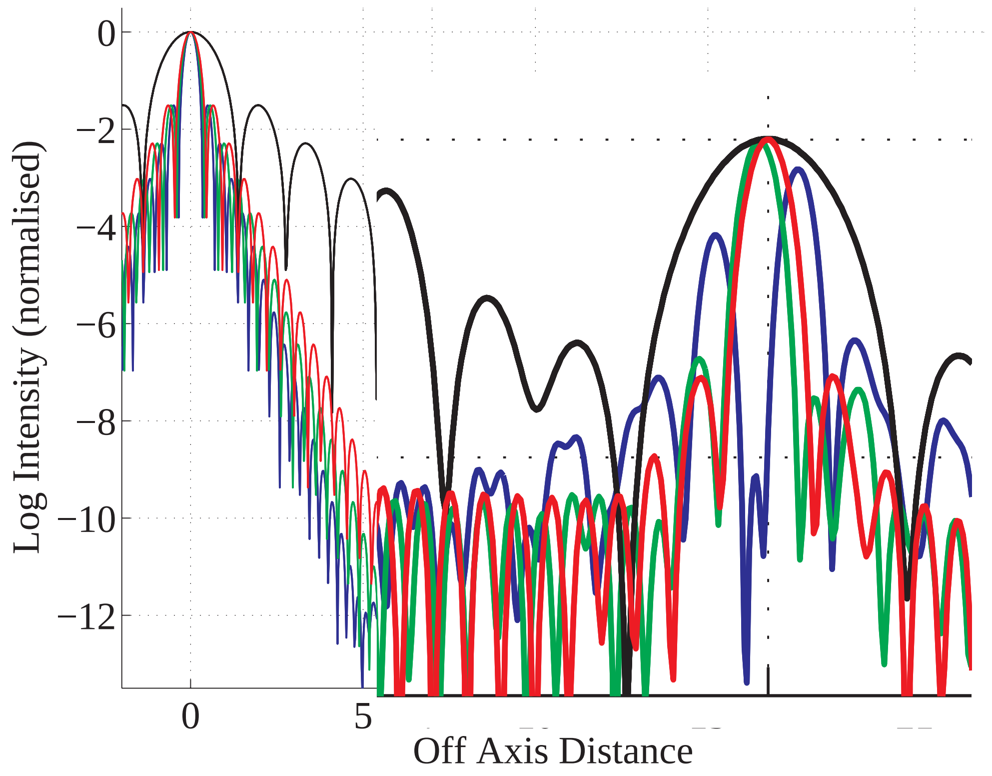
- Planets at 7λ/d and 21λ/d, each 10^{-10} brightness of host star
- 3 colours shown 760nm (blue), 872nm(green), 1000nm (red&black)



Units: λ/d (at 1000 nm)

Broadband

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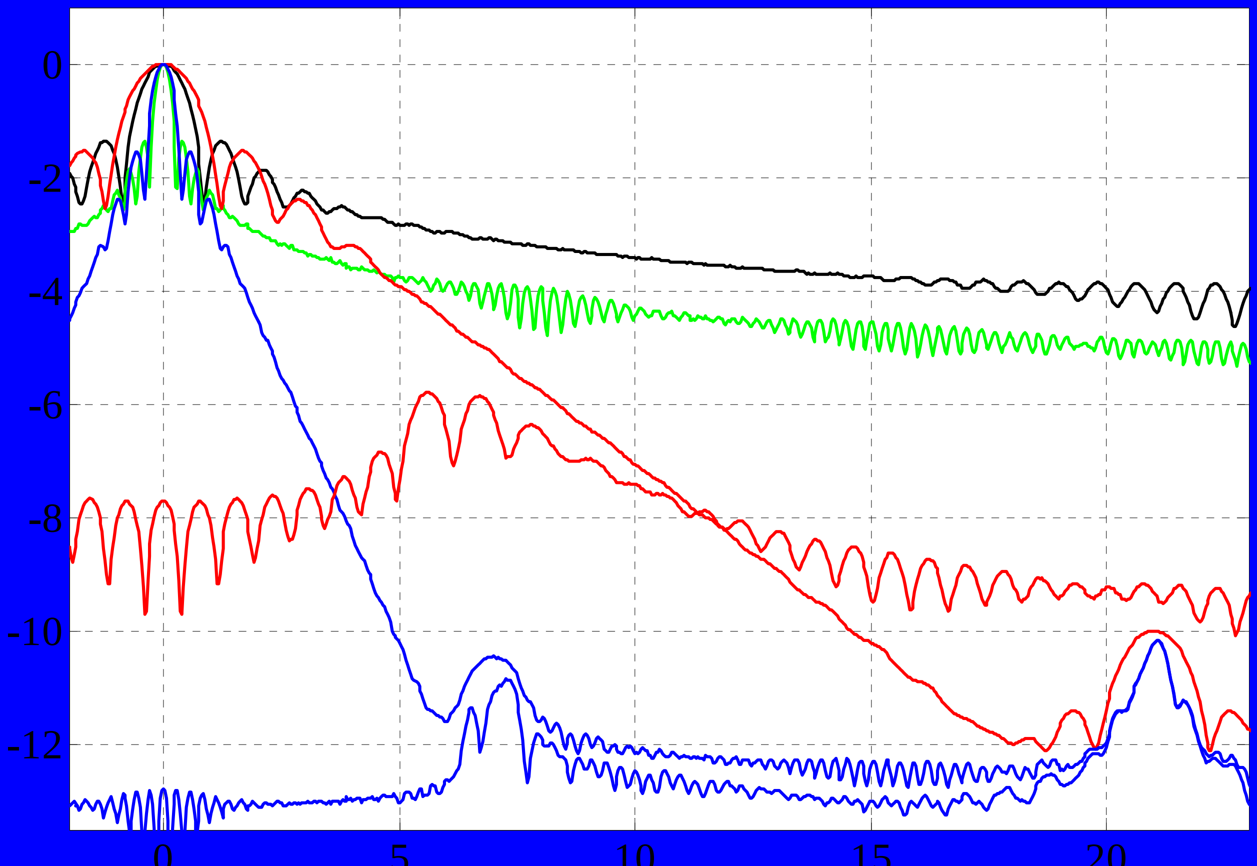
- V-band in 8 wavelengths and star stop



Error Sensitivity

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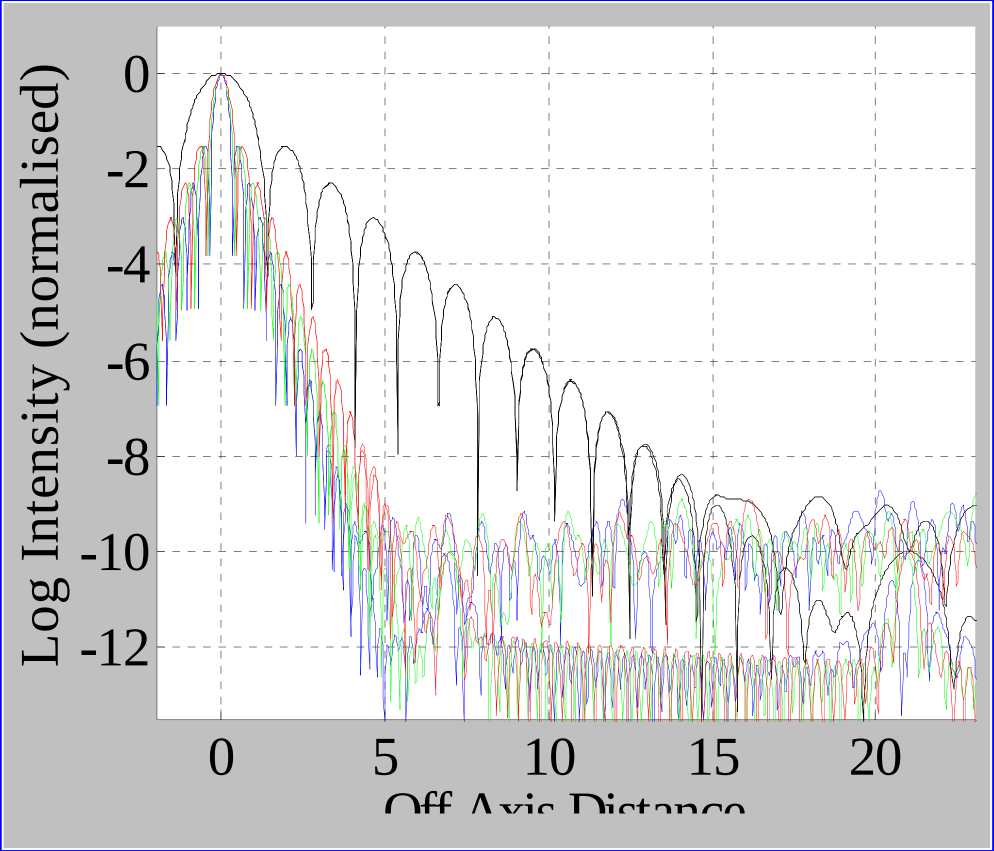
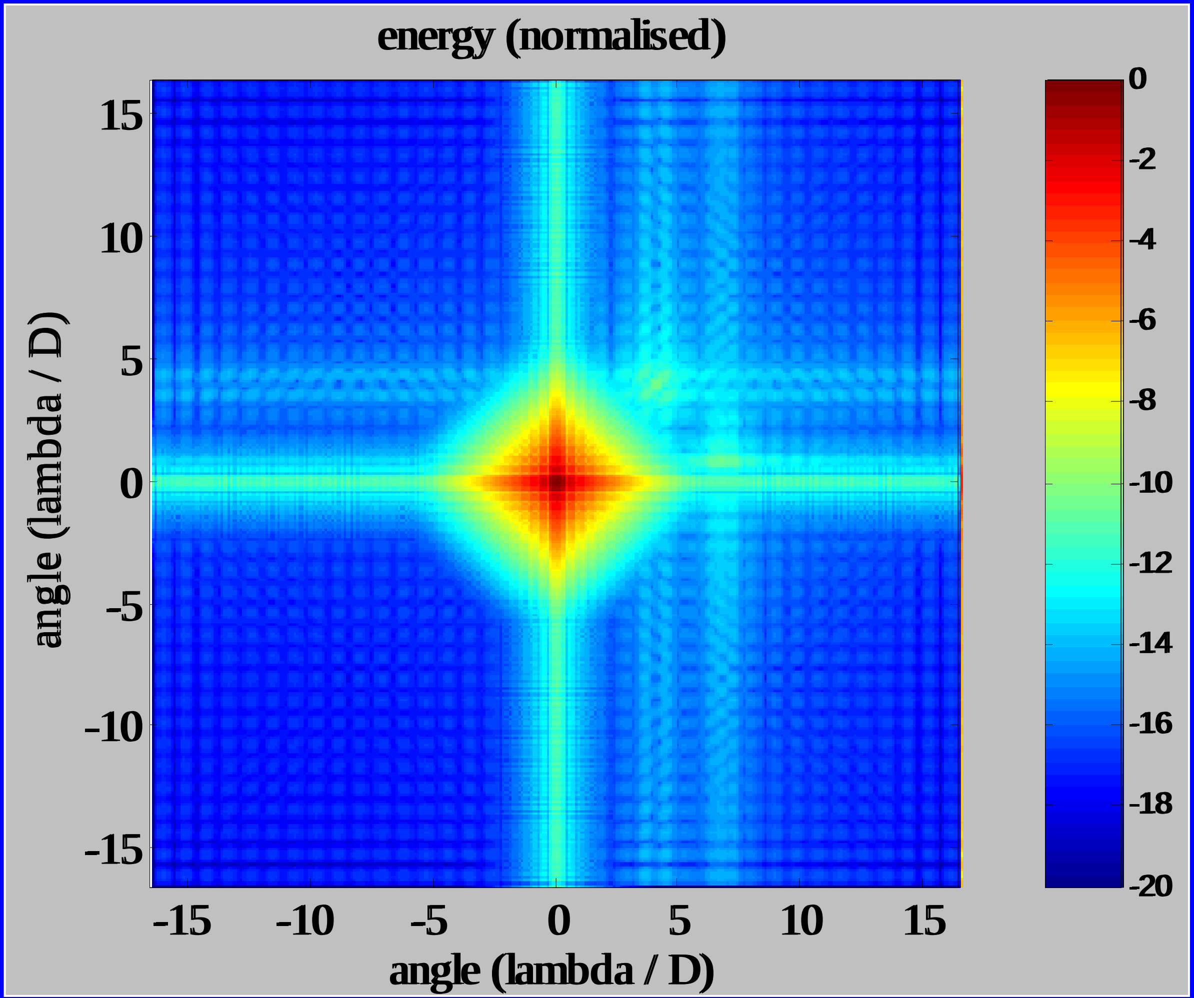
- Simulation of random amplitude errors
  - random amplitude error 10^{-3} max.
  - pixel size ~ 1 cm (results dependent on pixel size)



Two Dimensions



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Classical Coronagraph + PR

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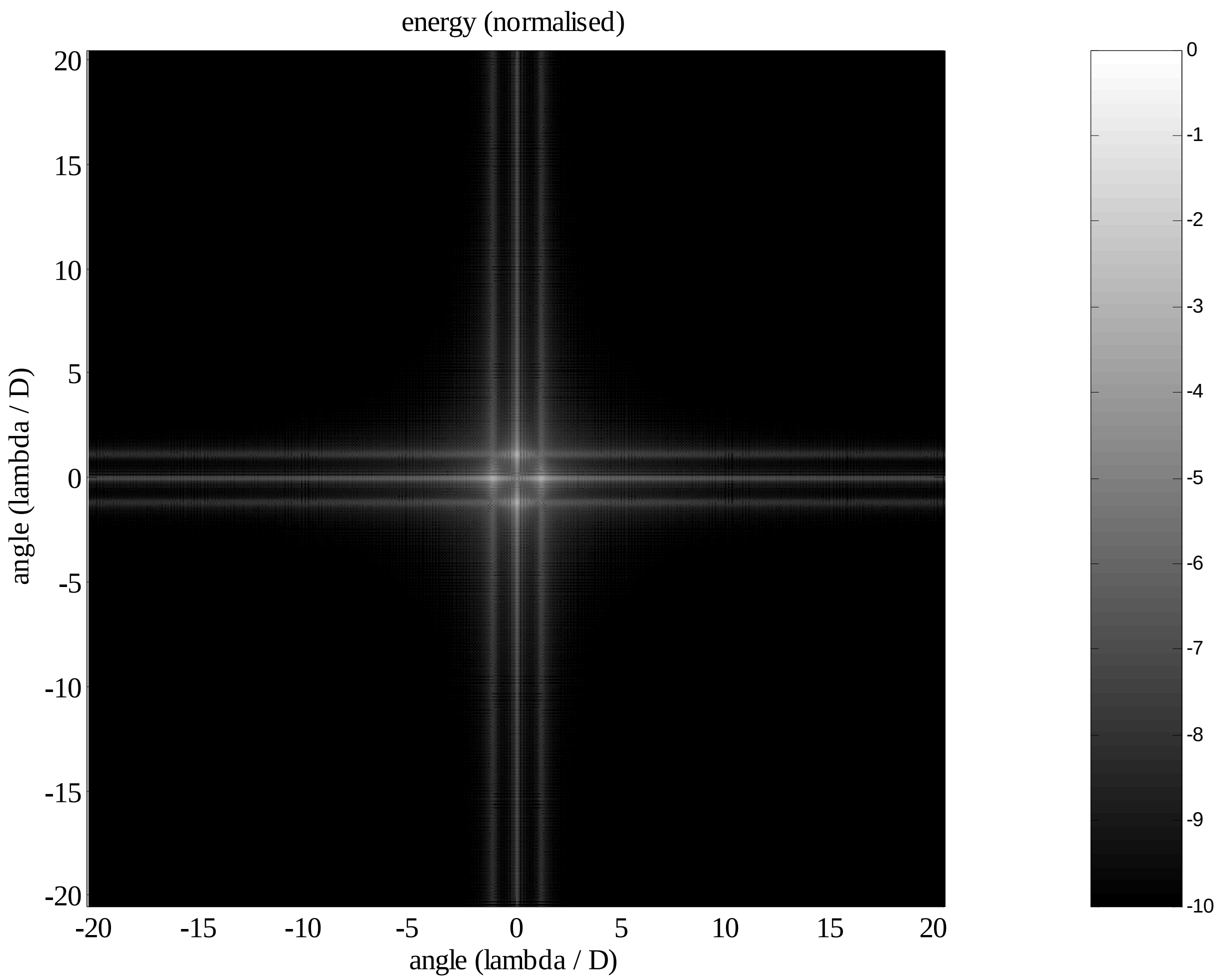

Off axis PSF (planet)

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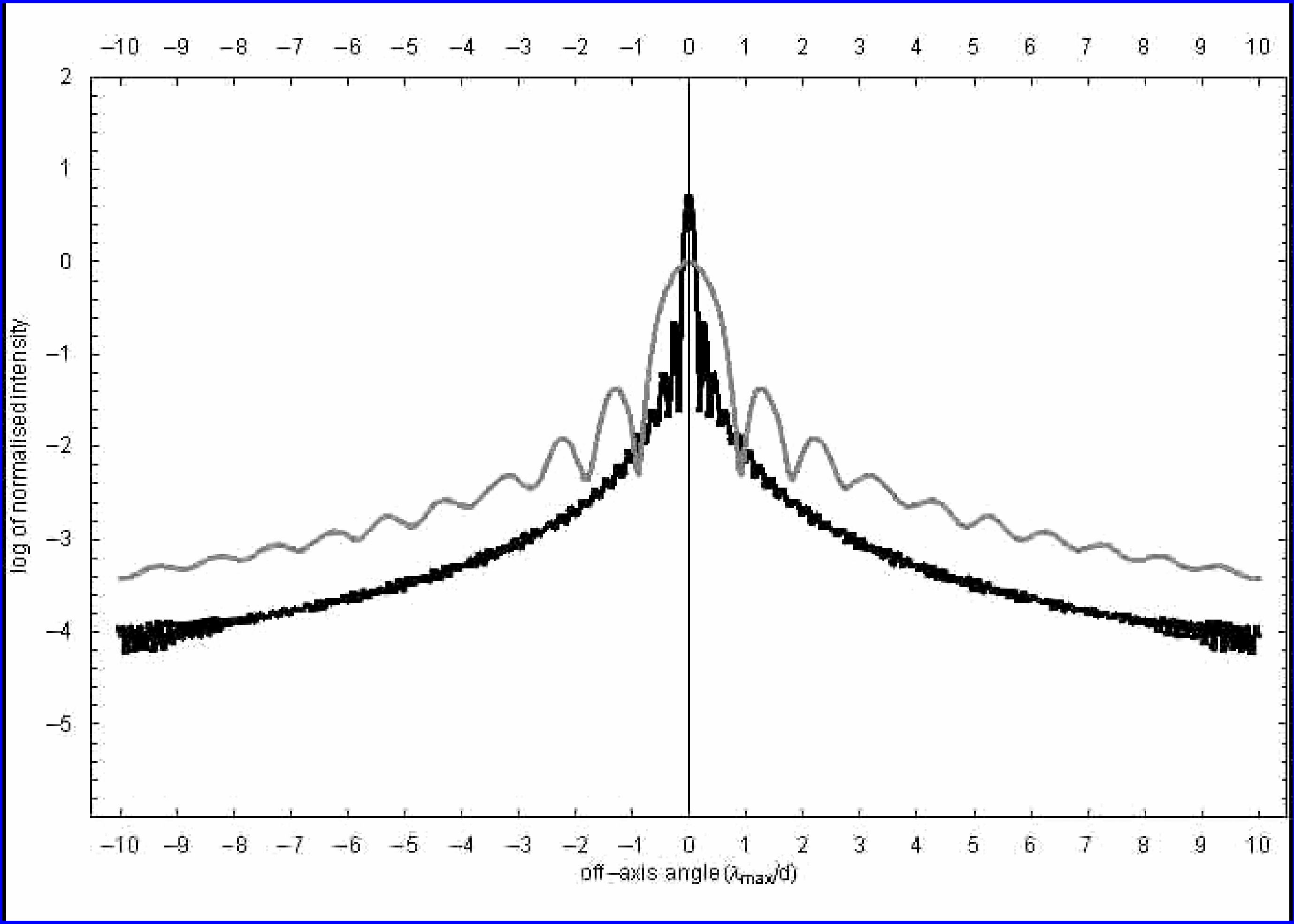

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Greenaway et al. (10 January 2005)