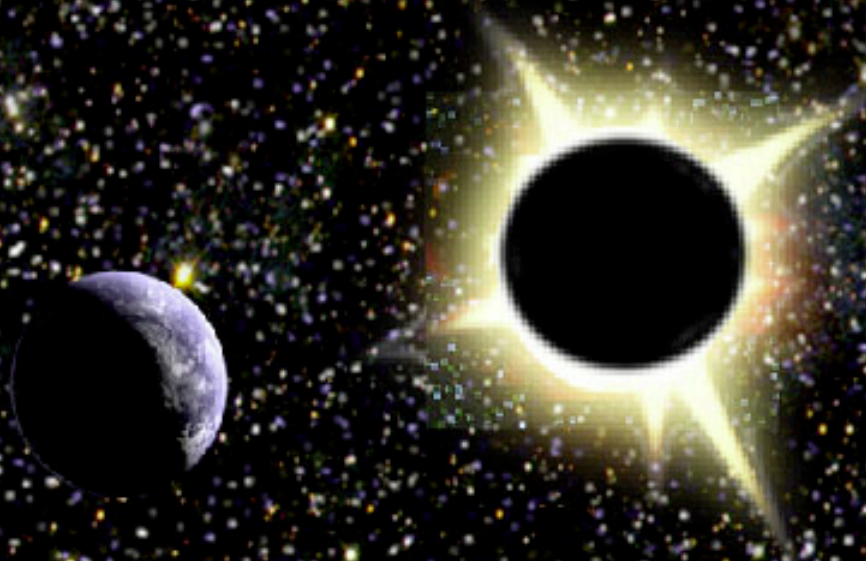
Coronagraphic Methods for Detection of Extra-Solar Planets



Richard G. Lyon
NASA/GSFC
February 25, 2004

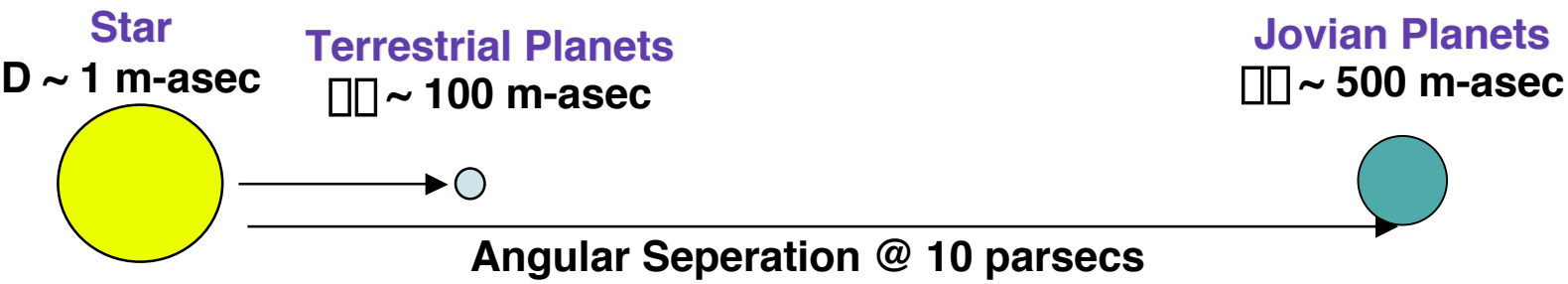
http://code935.gsfc.nasa.gov/cube%20Folder/OSCAR/index.html

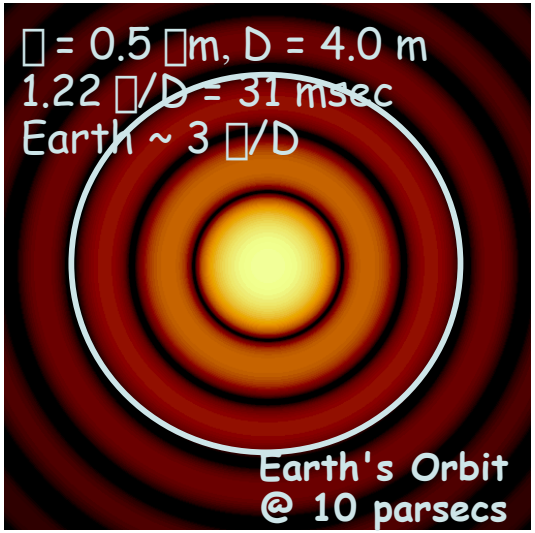
Contents

- Statement of the Problem
- Coronagraph vs Interferometer
- Why We Need A Coronagraph
- Types of Coronagraphs
  - ASA
  - Spergel/Kasdin/ Vanderbei
  - Internal Occulters (Lyot)
  - External Occulters
  - Hypertelescope
  - Shao Nulling Coronagraph
  - Labeyrie Corrector
- Sources of Error
  - Wavefront & Amplitude Errors
  - Polarization
  - Pointing & Shear
- Summary

R.G. Lyon
02/25/04

Statement of the Problem



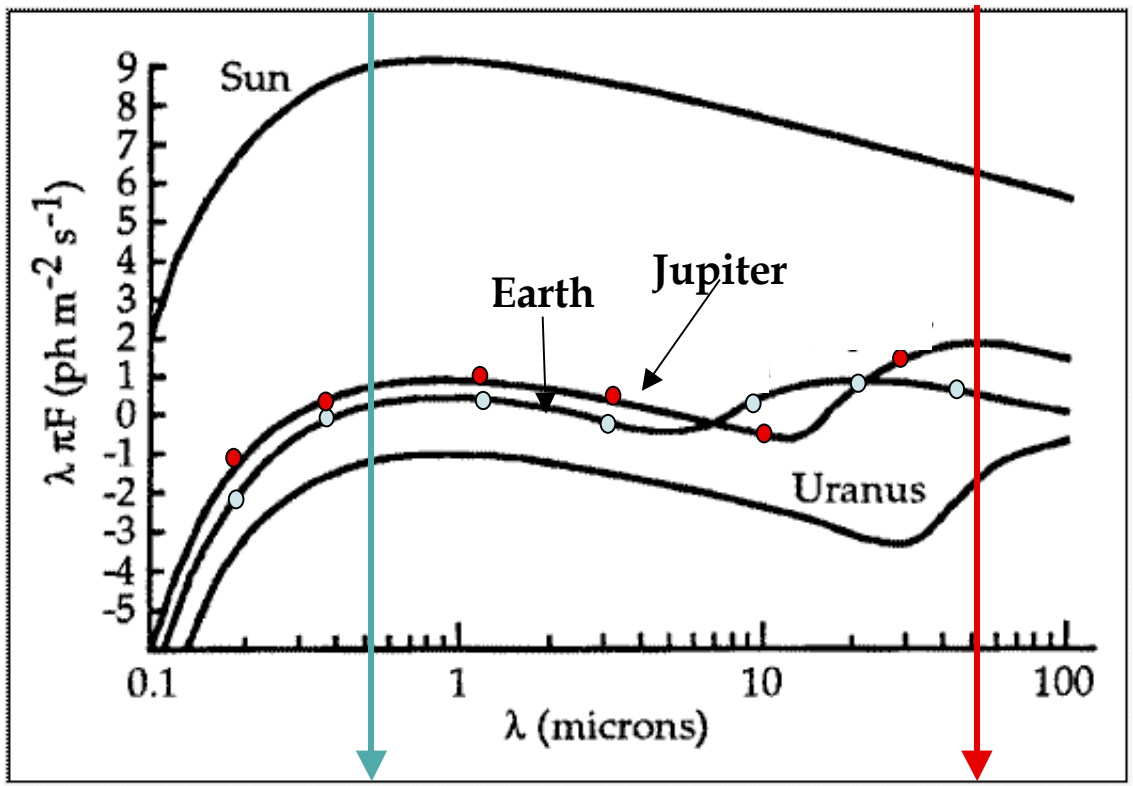


Detect / Characterize Terrestrial and Jovian Planets

- Planets have low Contrast wrt Stellar Source:
  - Diffraction
  - Wavefront & Amplitude Errors (Speckle)
  - Polarization Leakage
  - Wavefront Shear
  - Pointing
  - Exo-Zodiacal Light
- Two primary approaches under evaluation:
  - VIS Coronagraphy (Reflected Light) vs
  - IR Interferometry (Emitted Light)
- **Goal**: Distribution of planets, Detect Planet(s)
  Estimate orbital parameters
  Low and Medium Resolution Spectroscopy

R.G. Lyon
02/25/04

Coronagraph vs Interferometer ?

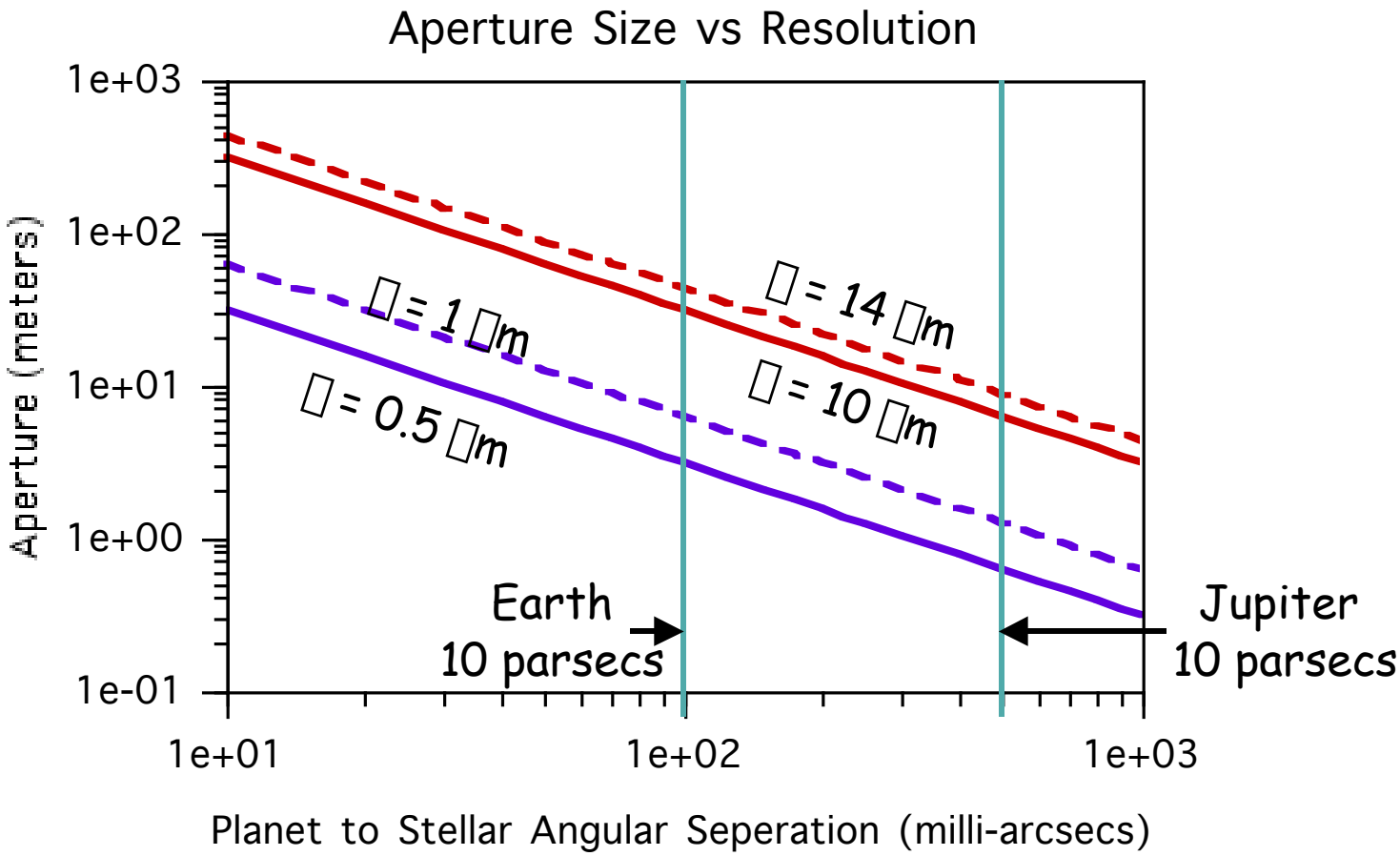


Visible Light Coronagraphy	IR Interferometry
Earth: $L_R \sim 10^{-10}$	Earth: $L_R \sim 10^{-7}$
Jupiter: $L_R \sim 10^{-9}$	Jupiter: $L_R \sim 10^{-5}$

IR-Interferometry => Advantage in terms of Luminosity Ratio

R.G. Lyon
02/25/04

However ?



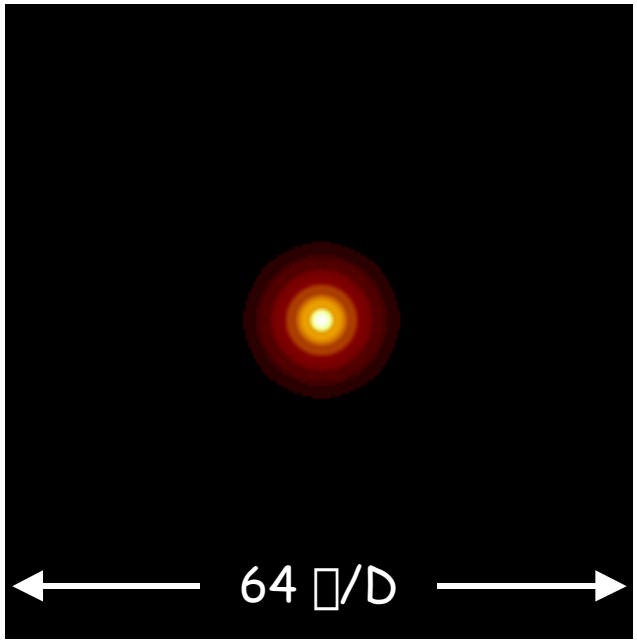
Visible Light Coronagraphy	IR Interferometry
Earth: D ~ 3 - 6 meters	Earth: B ~ 30 - 43 meters
Jupiter: D ~ 0.62 - 1.25 meters	Jupiter: B ~ 6 - 9 meters

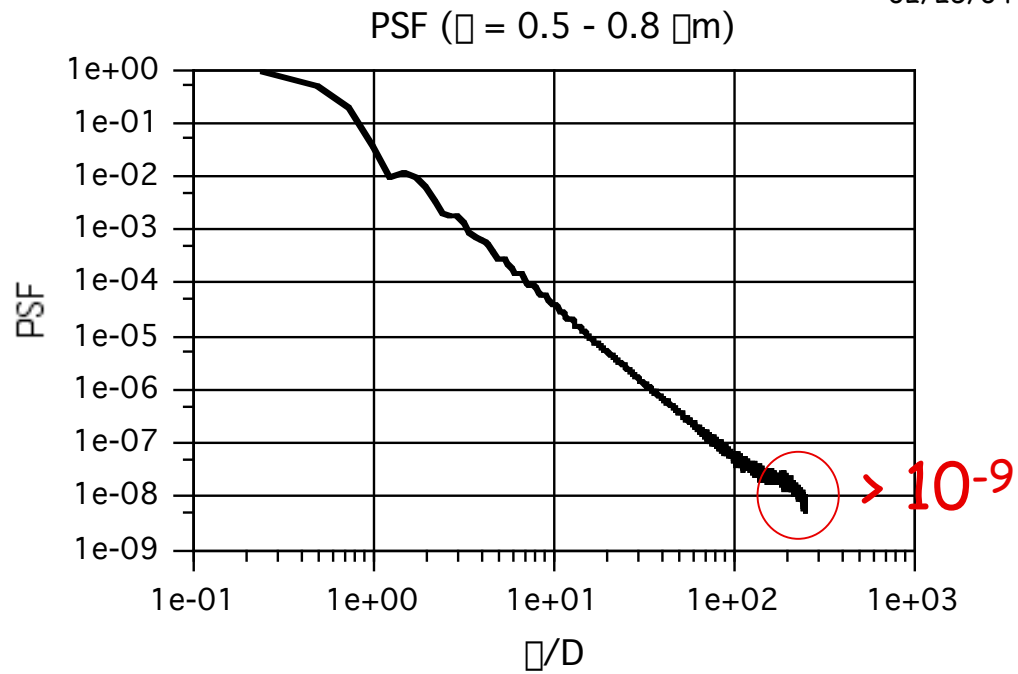
VIS Coronagraphy => Advantage in terms of Aperture Size

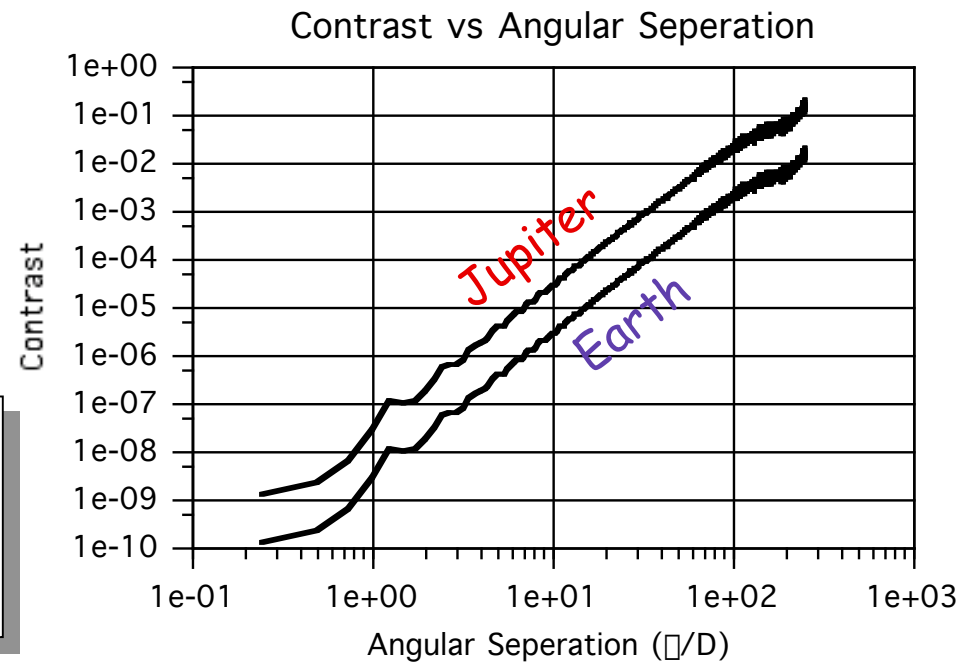
R.G. Lyon
02/25/04

Why We Need A Coronagraph ?

Why not a conventional Telescope ?



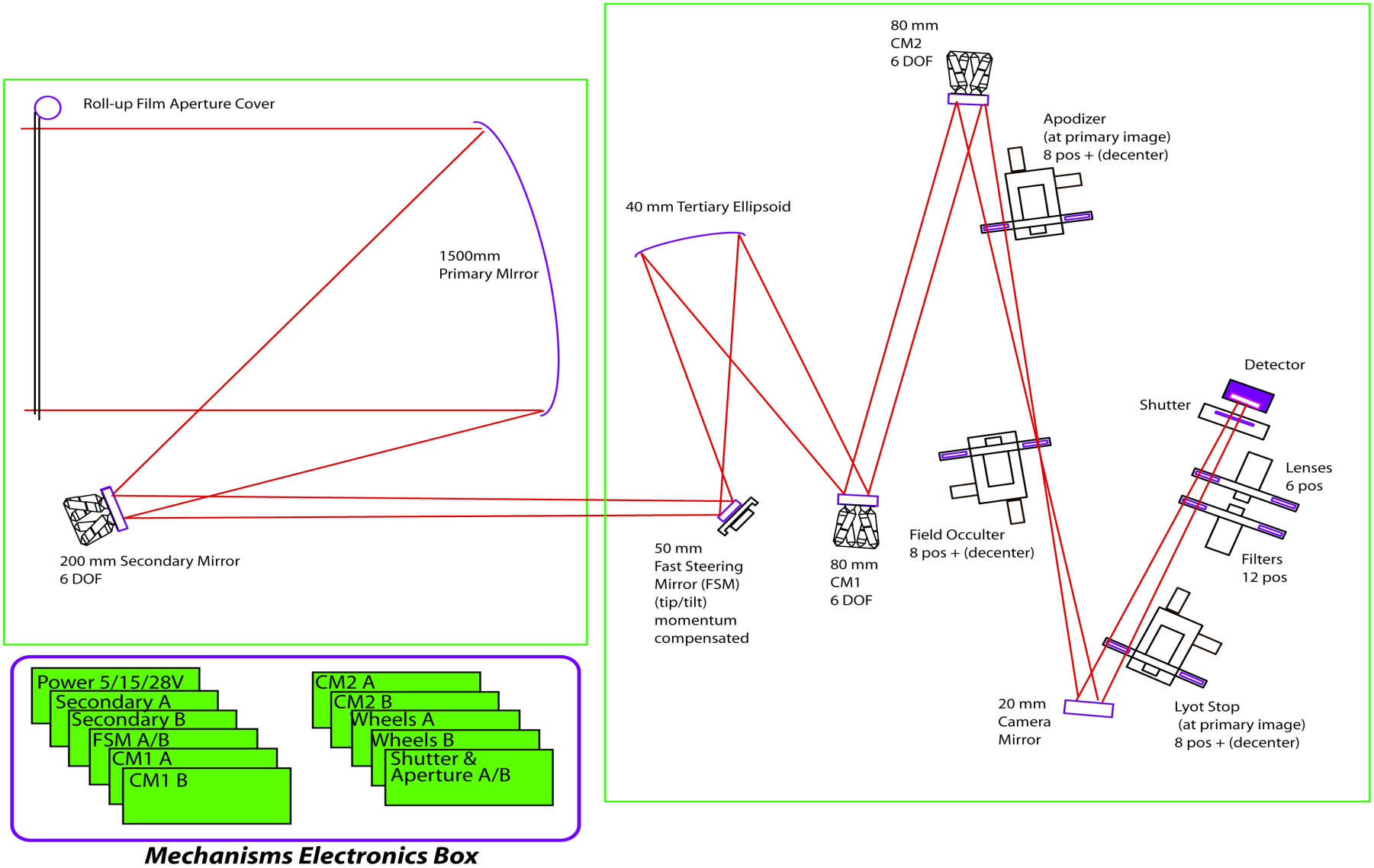




The ratio of the planetary flux to stellar diffracted flux has Contrast < 1 out to ~1000 λ/D !

R.G. Lyon
02/25/04

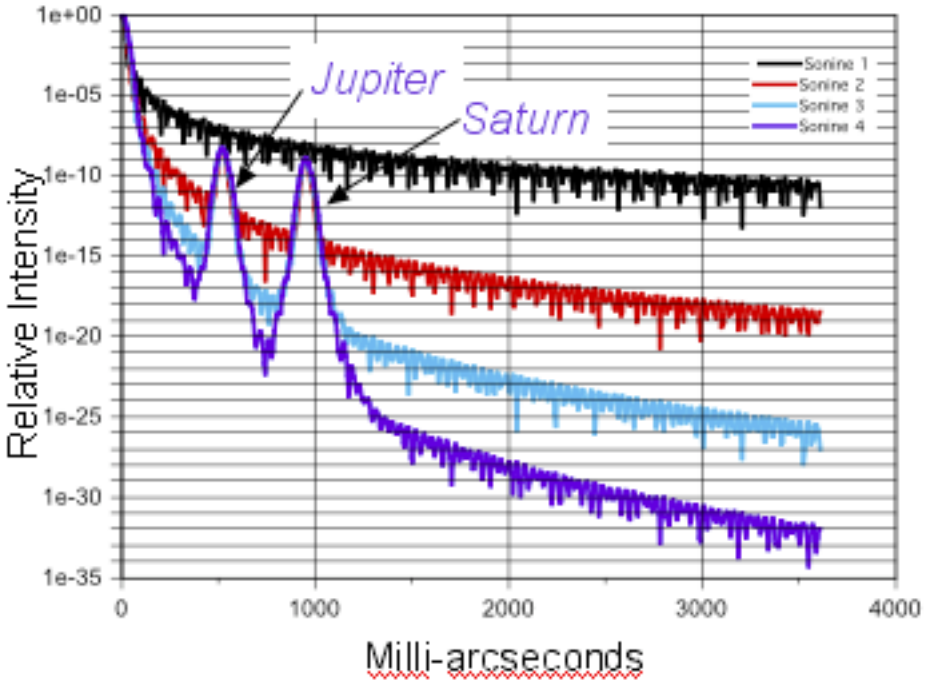
What is a Coronagraph ?

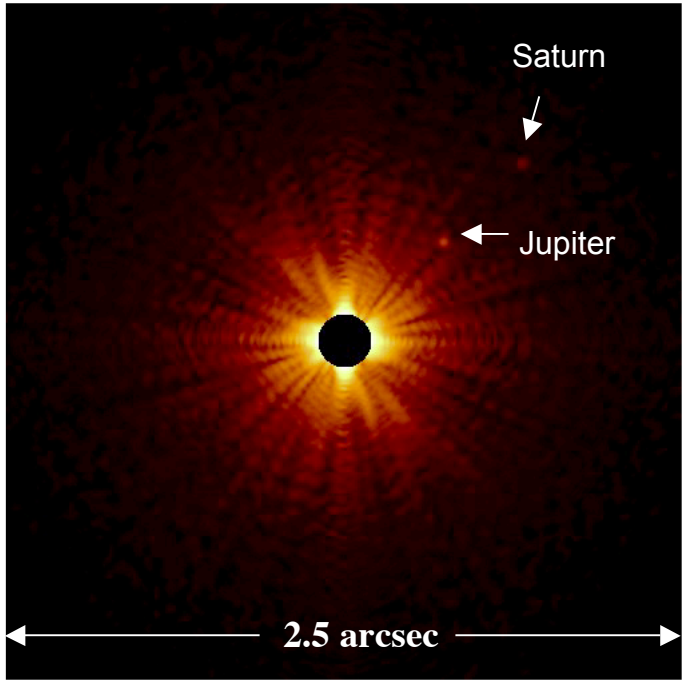


Mechanisms Electronics Box

R.G. Lyon
02/25/04

What does a Coronagraph do ?





Coronagraph increases Contrast of Planet wrt Stellar Source

Tapers wings of Point Spread Function in controlled fashion

Sensitive to:

- Wavefront & Amplitude Errors (Speckle)
- Polarization Leakage, throughput
- Wavefront Shear & Pointing
- Manufacturing Errors, Exo-Zodiacal Light
- Vector vs Scalar Diffraction

R.G. Lyon
02/25/04

Scope of Studies

- *Compare/Contrast Exo-Planetary Imaging Techniques*
- Develop analytical/computational models for:
  - Apodized Square Aperture =>Sonine, Jacquinot, Prolate-Spheroid
  - Hard & Soft-Edge Lyot Coronagraph
  - Spergel/Kasdin/Vanderbei Pupils
  - External Occulter (UMBRAS)
  - Hypertelescope
  - Labeyrie Corrector
  - Shao Nulling Coronagraph

Cross-validation w/JPL Models is underway

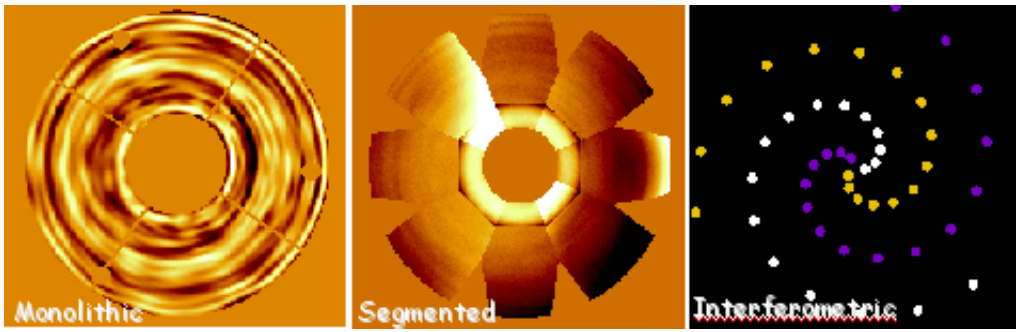
- Calculate Sensitivities of: $\Delta(C,SNR) = \dfrac{\partial(C,SNR)}{\partial(R,\Delta,\Delta_{LO},\Delta_{MED},\Delta_{HI},\Delta_{Amp},\Delta_{Pol},\Delta_{Point},\Delta_{Vector},\ldots)}$
  - Spectral Bandpass
  - Wavefront Error (low-, mid- and hi-spatial frequency)
  - Optical misalignments, Aberrations
  - Amplitude errors (reflectivity/transmission)
  - Polarization / Vector Effects
  - Pointing error (static, jitter)
- Develop Contrast, SNR, Coverage and # of stars, Metrics
  - quantitatively compare techniques on ***equal footing*** !
  - Develop Error Budgeting Formalism
- Study is Ongoing.

R.G. Lyon
02/25/04

Optical Modeling

Optical Systems Characterization and Analysis Research Software (OSCAR)

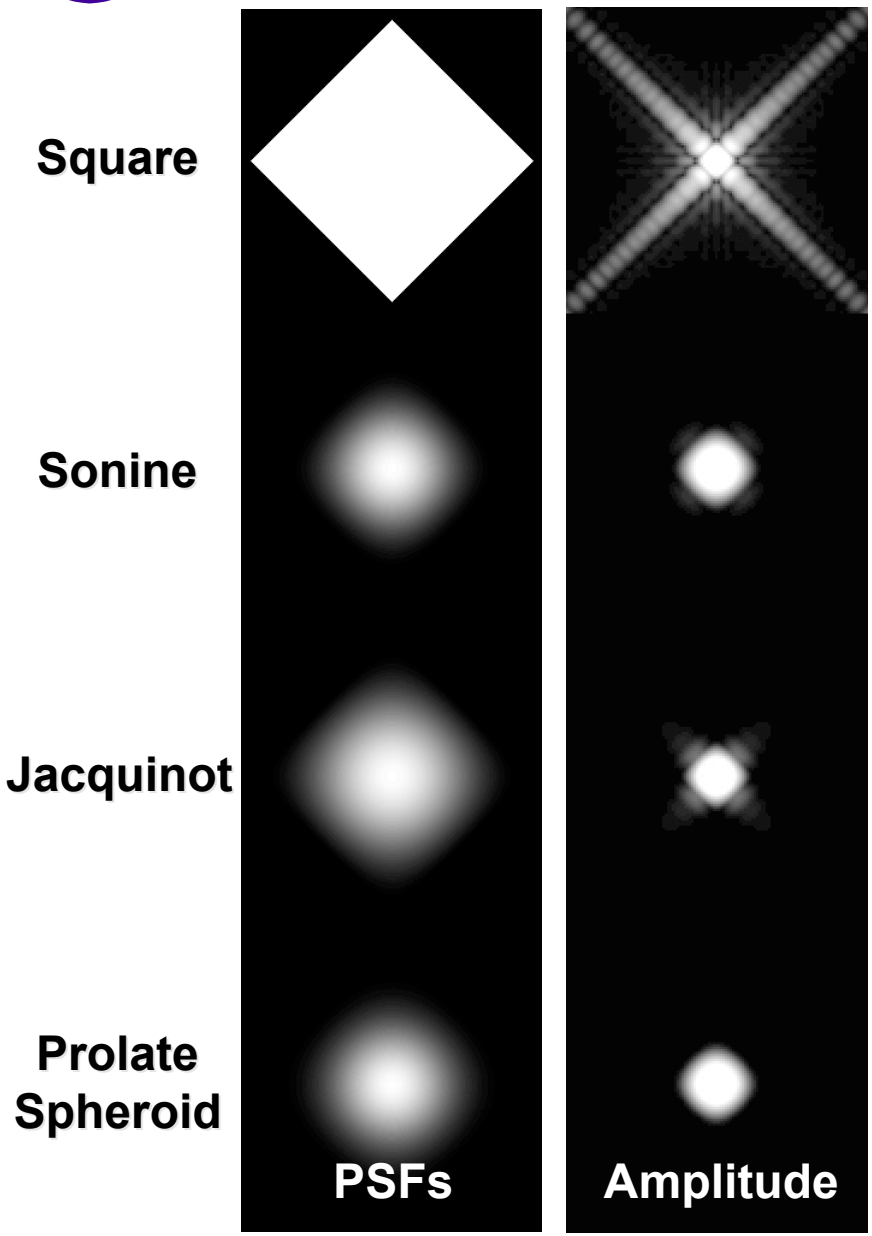
- **OSCAR Capabilities:**
  - Single Plane Diffraction
  - Multiple-Plane Scalar & Vector Diffraction (Fresnel).
  - Vector Optical Helmholtz Solvers
    - 2D and 3D models
    - Tetrahedral Mesh - edge based approach (div E = 0)
  - 3D Vector Model Coupled to Systems Model via Component Transfer Functions
- **OSCAR Models:**
  - Amplitude & Phase Errors, Polychromatic effects
  - Coatings, Misalignments, Deformations, Material Inhomogenous effects, Wavefront sensing and Optical Control
- **OSCAR:**
  - "C" and "C/MPI" versions, Beowulf cluster (Medusa)
  - Disclosed thru TCO, Currently undergoing release process
  - 3 Companies have requested use of OSCAR

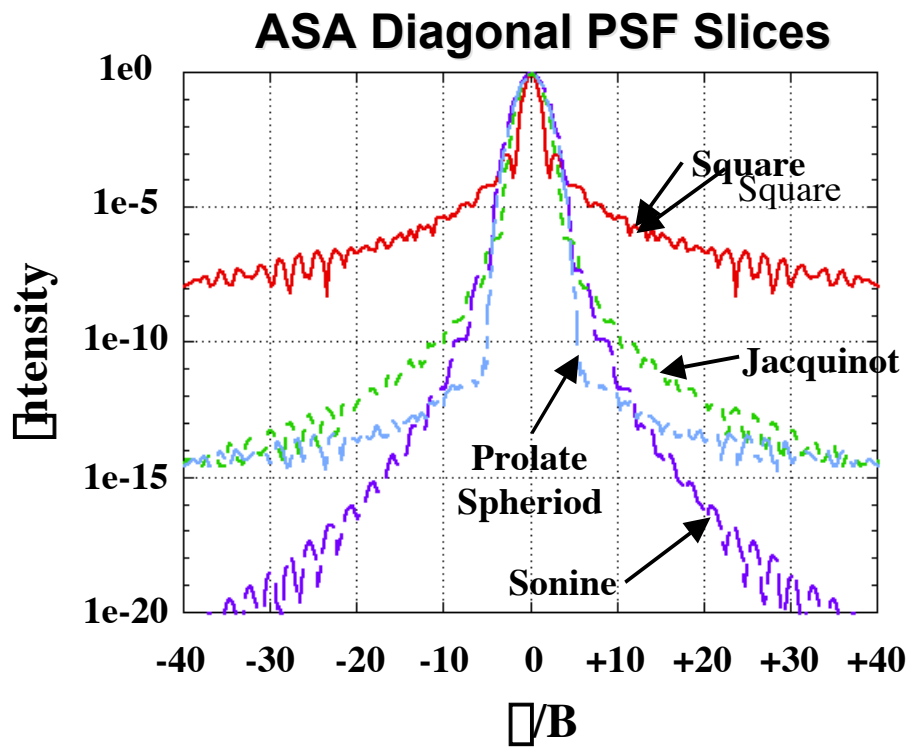


Apodized Square Aperture (ASA)

ESPI - Extra-Solar Planet Imager Proposed Concept

R.G. Lyon
02/25/04





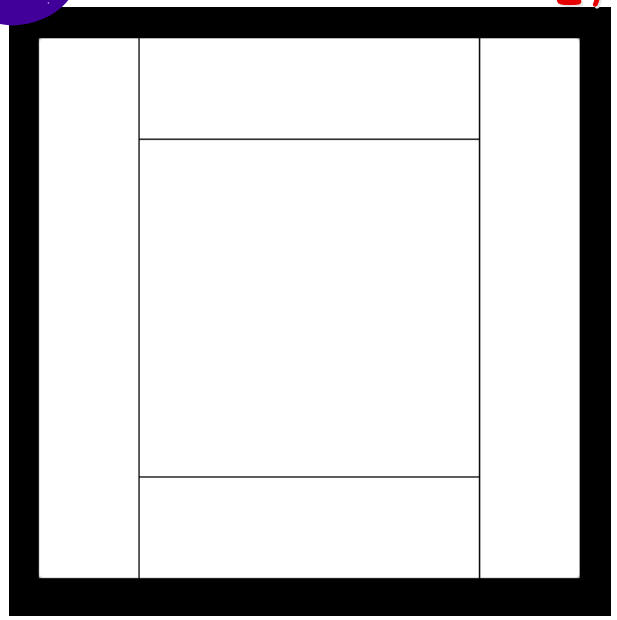
PSFs: =0.6 m, =0.2 m.

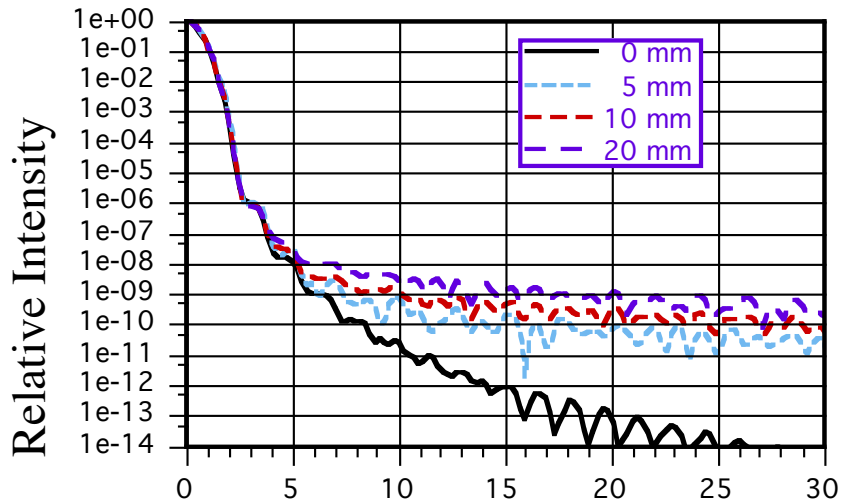
PSFs on same log scale and the Amplitude functions on same linear scale.

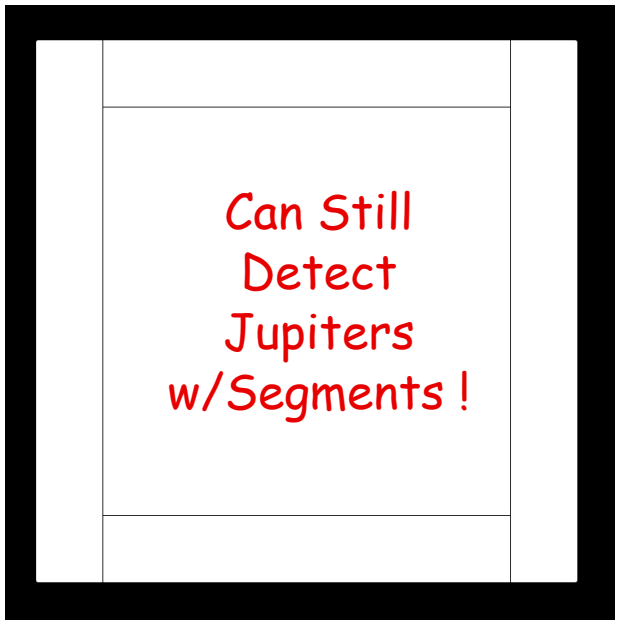
R.G. Lyon
02/25/04

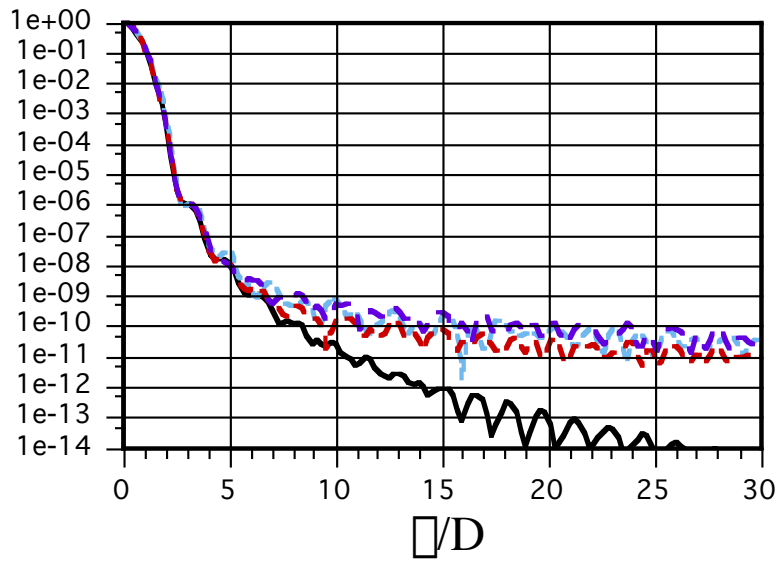
Apodized Square Aperture (ASA)

Effect of Segmenting PM





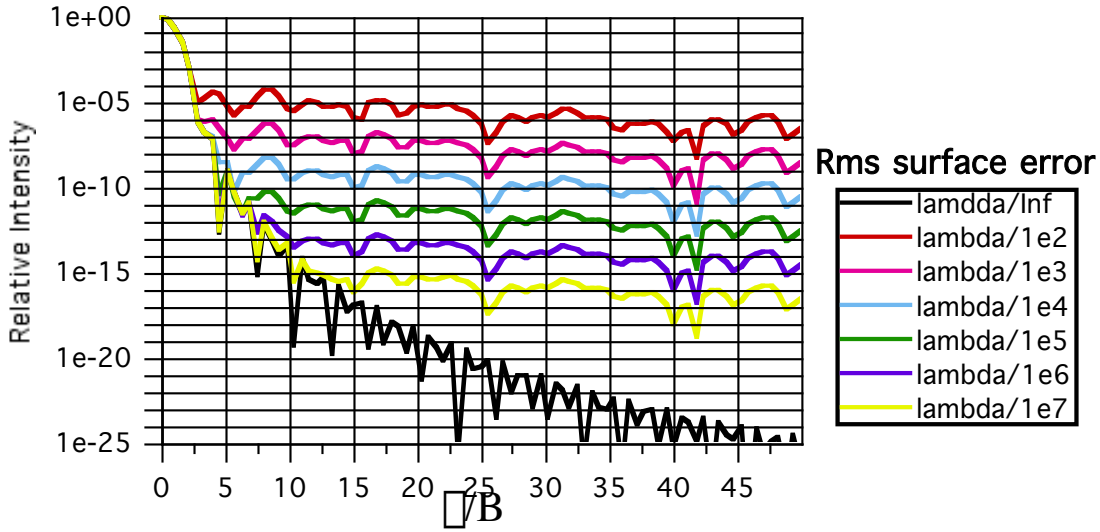




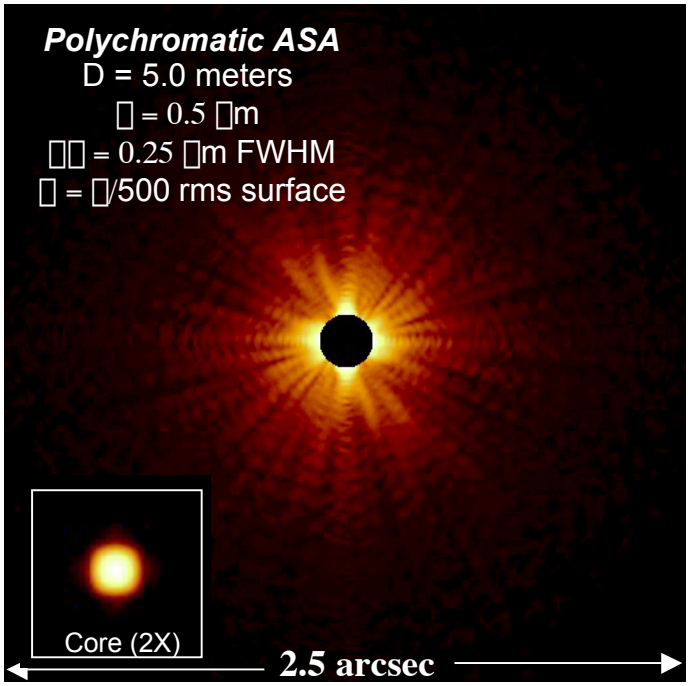
R.G. Lyon
02/25/04

Apodized Square Aperture (ASA)

Effects of WFE



Random PSD(f)
- Slope = -2.00
- Monochromatic
- Knee freq = 0.1 cyc/ap
- 4 order Sonine apodization



Wavefront Errors Dominate

Nearly Independent of Method

Major Result of ESP NRA Study:

(Woodruff, Lyotn et.al.)

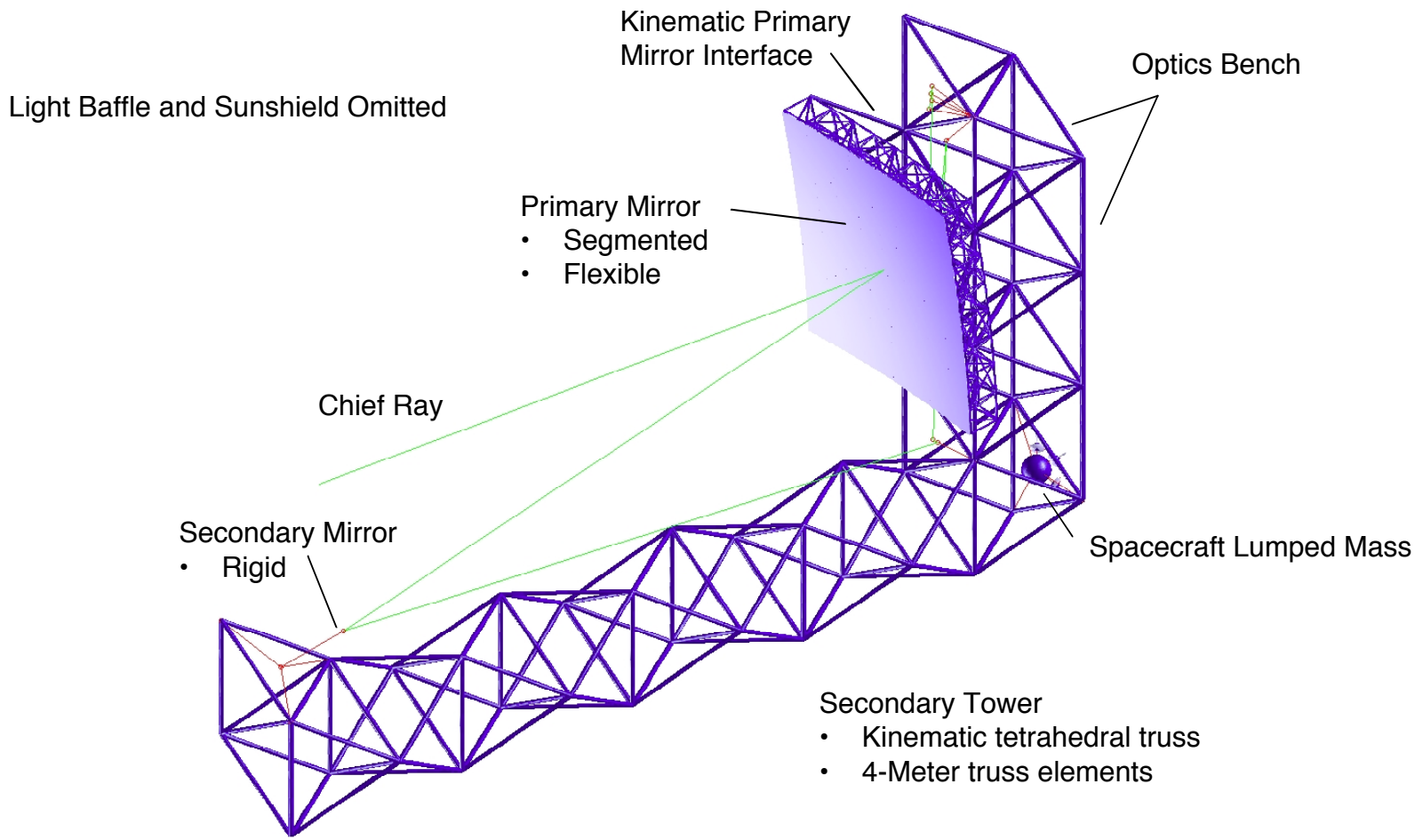
Jupiters => WFE ~ /2000 rms

Earths => WFE ~ /10,000 rms !

R.G. Lyon
02/25/04

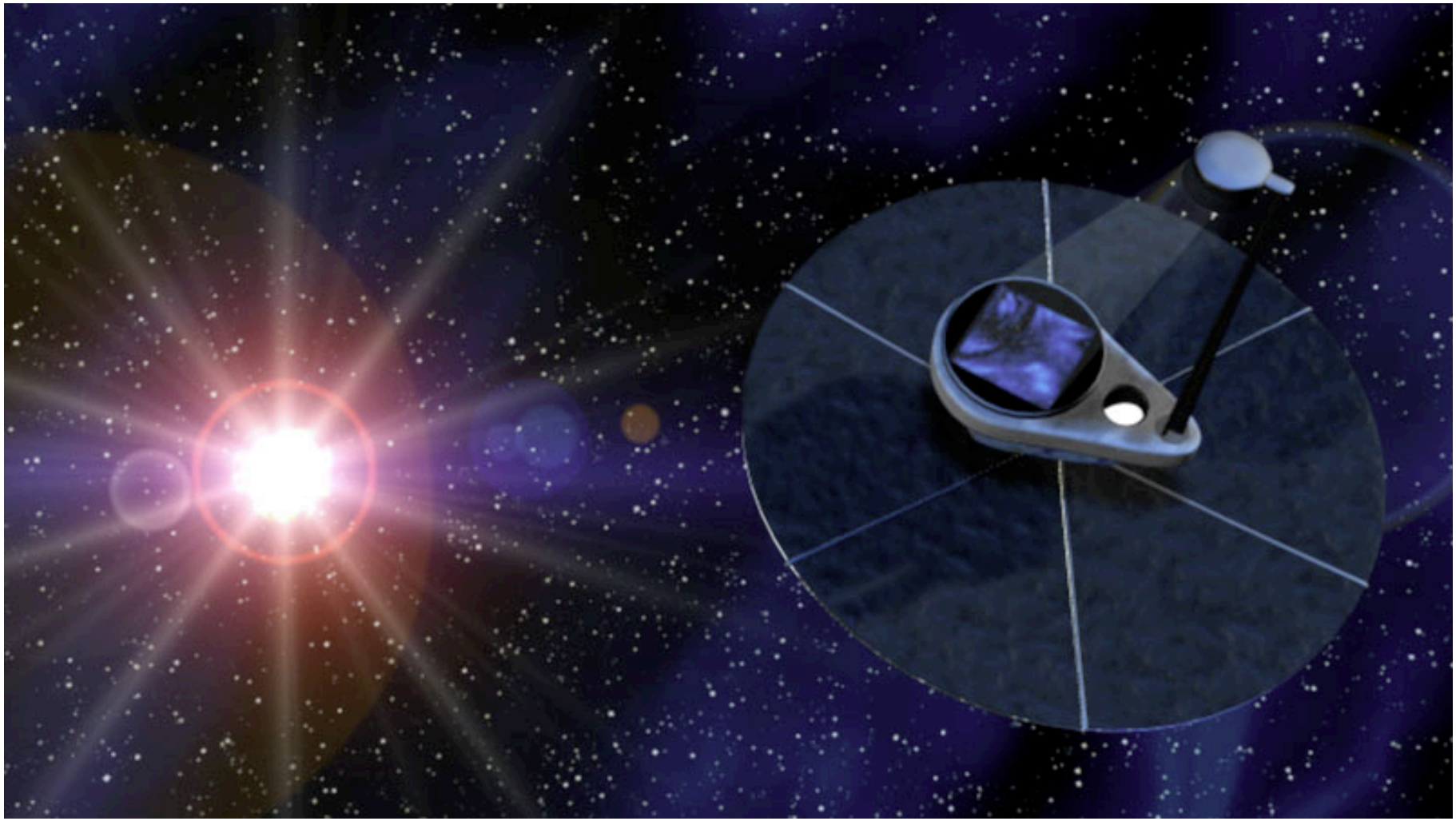
Apodized Square Aperture (ASA)

Structural Model



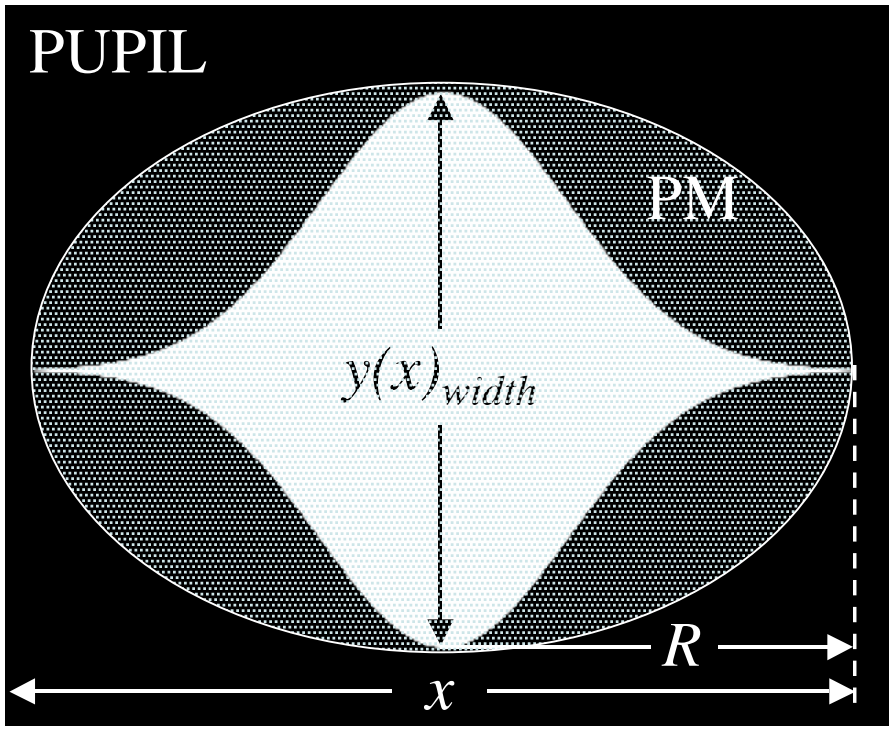
R.G. Lyon
02/25/04

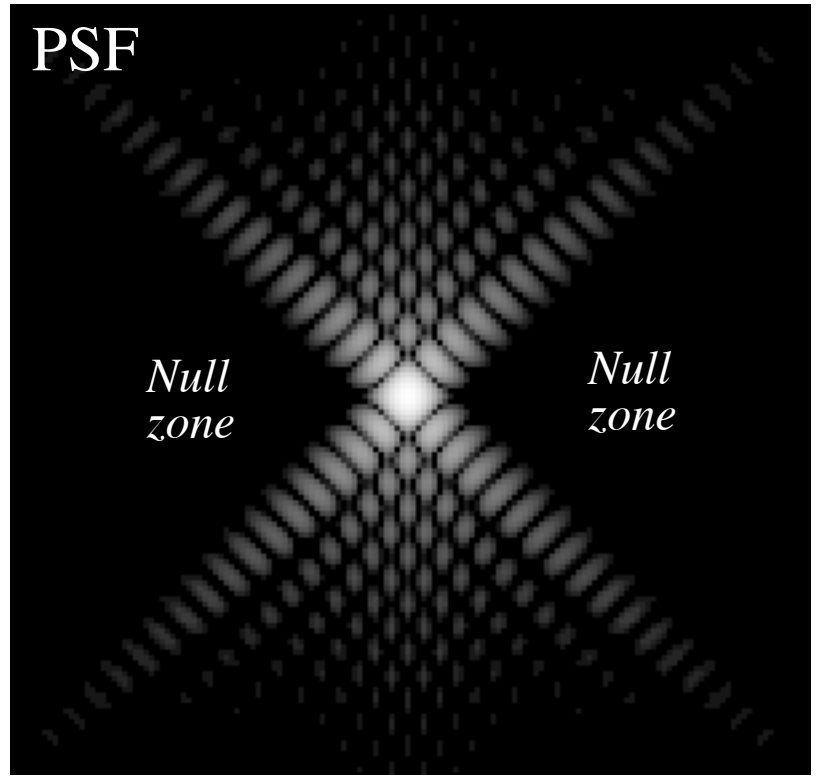
Apodized Square Apertures



Spergel/Kasdin Pupils

R.G. Lyon
02/25/04



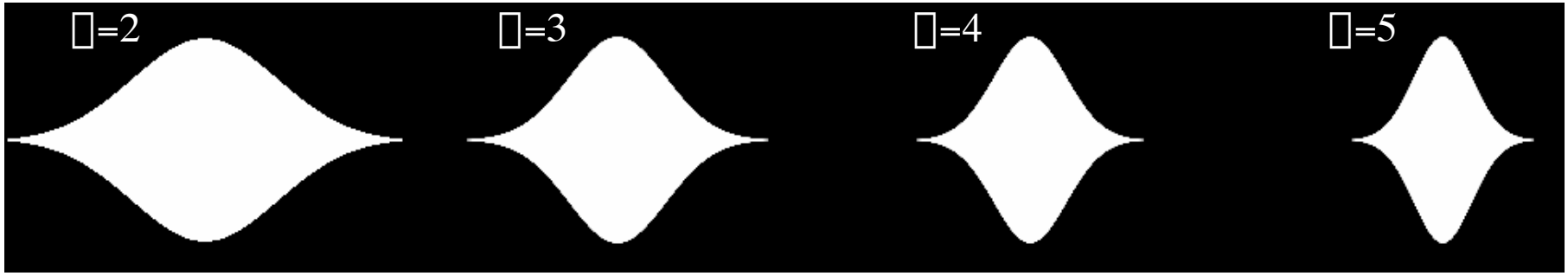


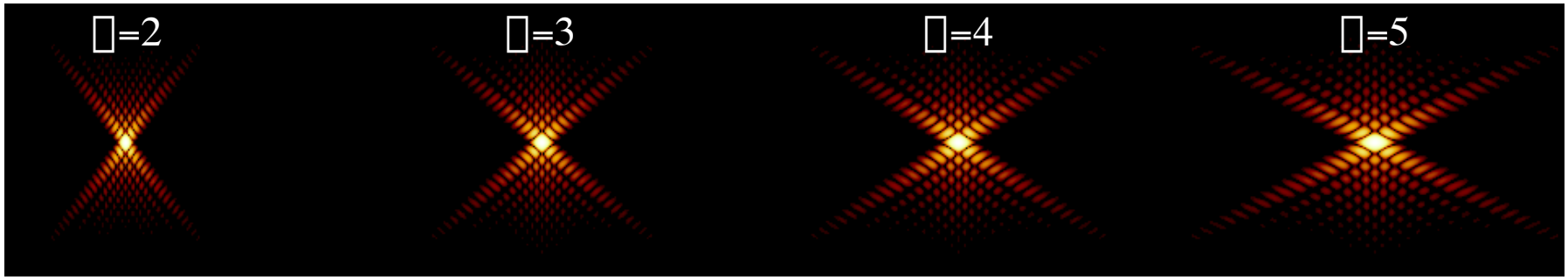
- Shaped pupil: $y(x)_{width} = R\left[\exp\left(-\left(\frac{x}{R}\right)^2\right) - \exp(-1)\right]$ *with* $-R \le x \le +R$
- Shaped pupil would fit onto elliptical PM of: $2R \times R\{1-\exp(-1)\}$

Spergel/Kasdin Pupils

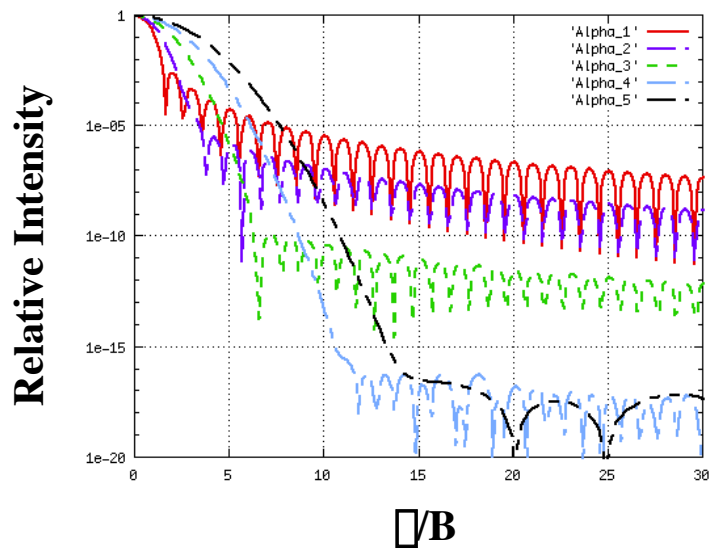
Apertures and PSFs

R.G. Lyon
02/25/04





PSF Slices in x-direction



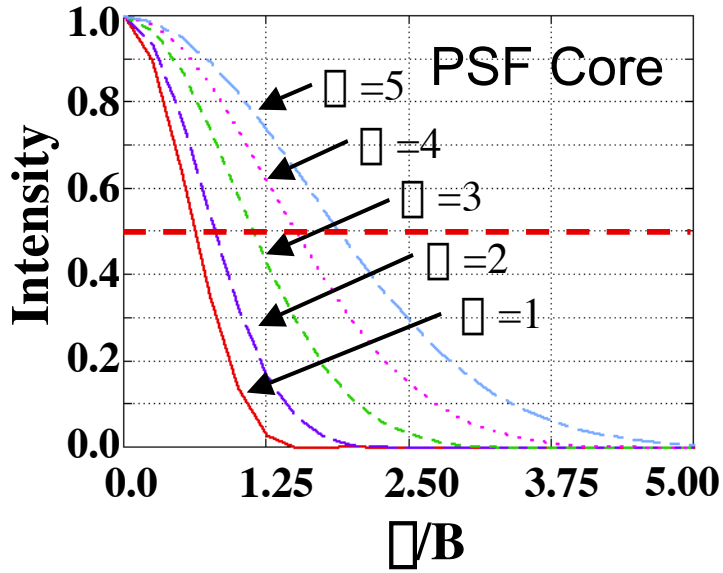
As is increases:

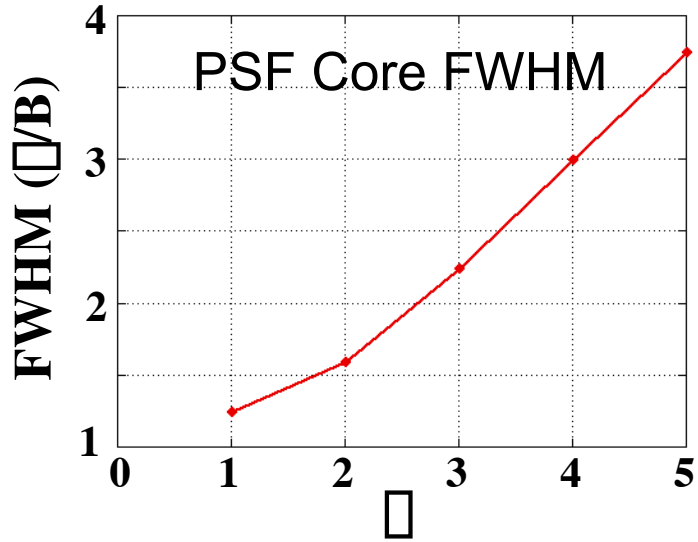
- Pupils narrow in x
- Null zones decrease in area
- Null depth is deeper
- PSF core broadens

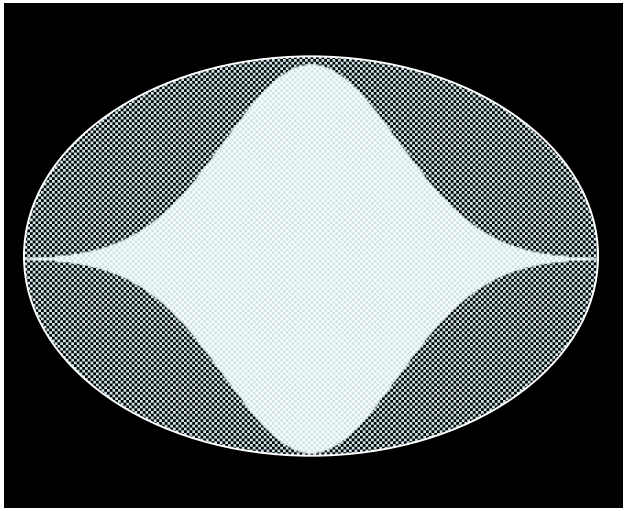
R.G. Lyon
02/25/04

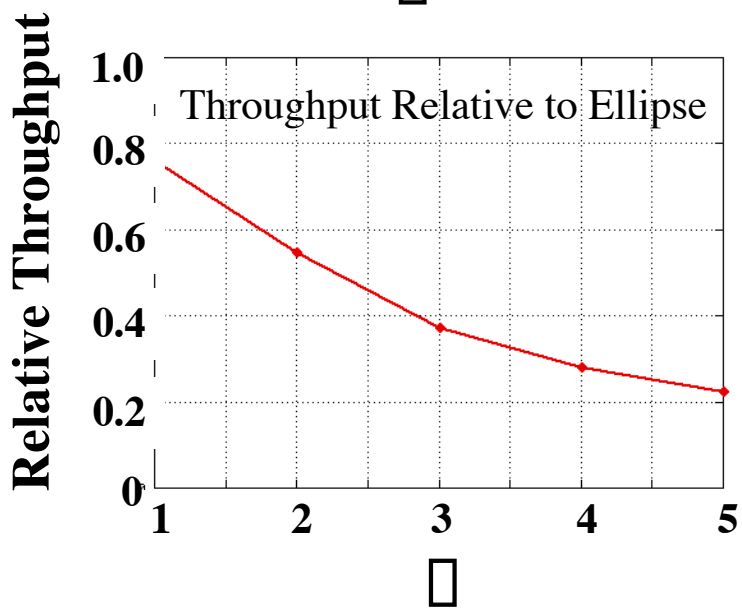
Spergel/Kasdin Pupils

Effect of □



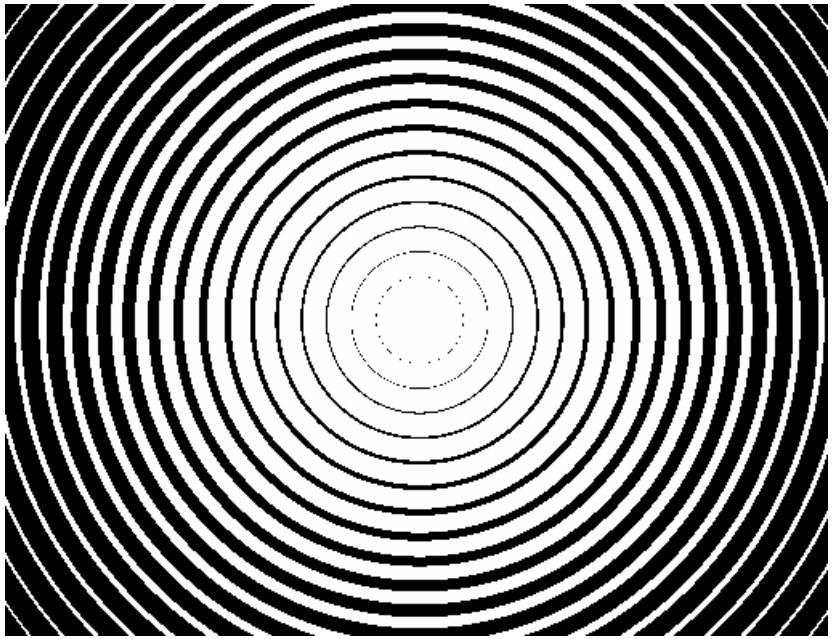


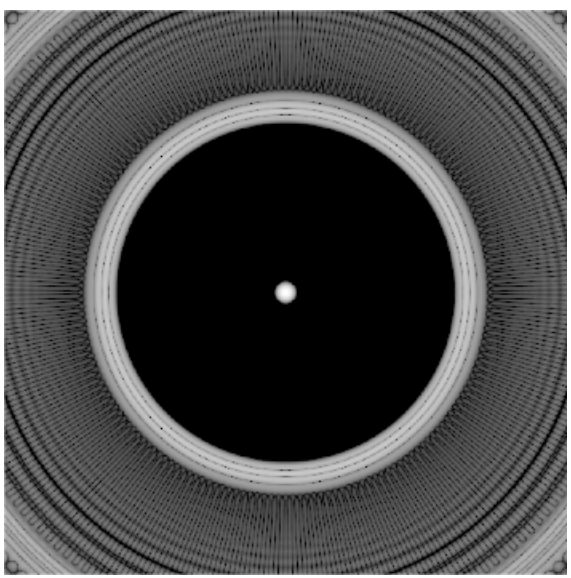




Vanderbei Apertures

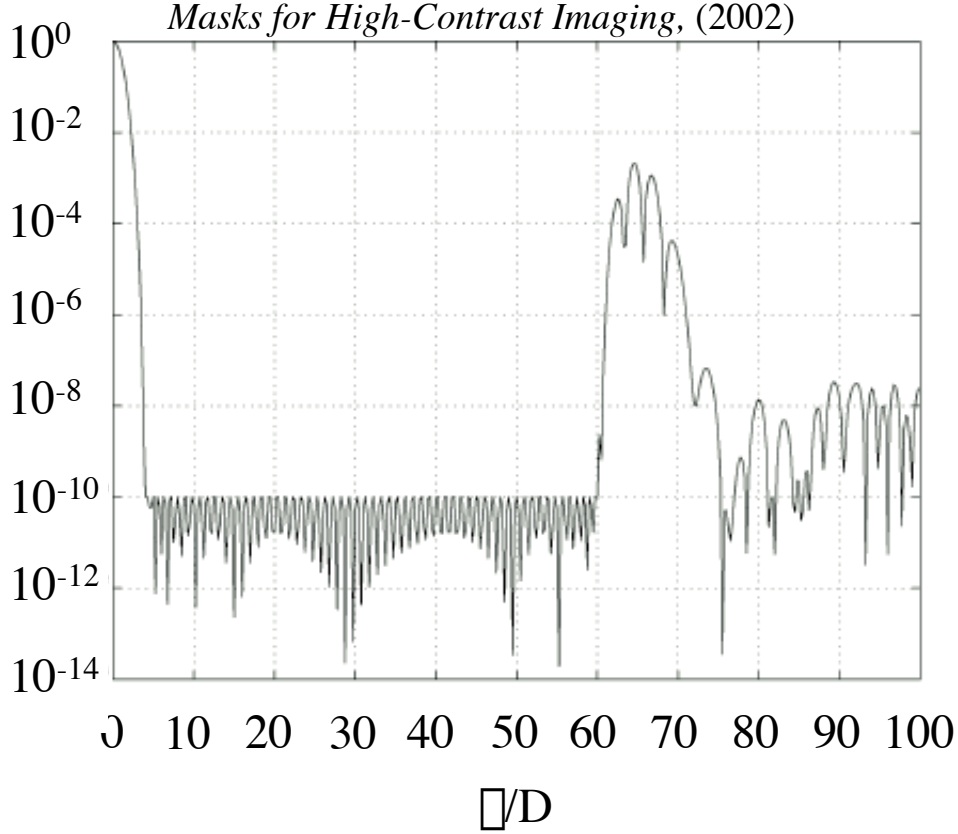
R.G. Lyon
02/25/04





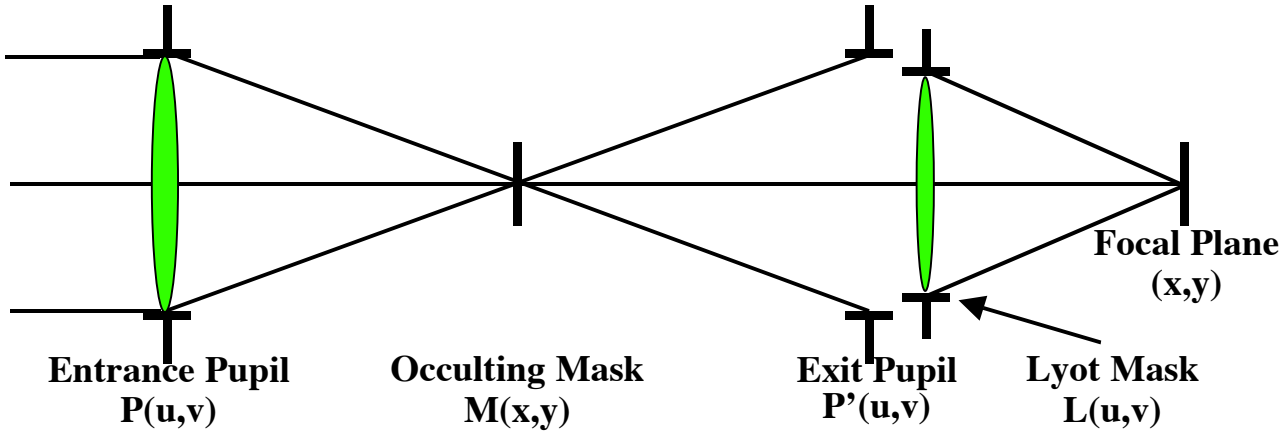
Series of Concentric Blocking Rings
Like Fresnel Zone Plate / Circular Grating
Needs Mounting Spiders
Low Throughput
Manufacturability ? 2nd order diffraction ?

R. Vanderbei, D.Spergel, J.Kasdin, *Spiderweb Masks for High-Contrast Imaging*, (2002)

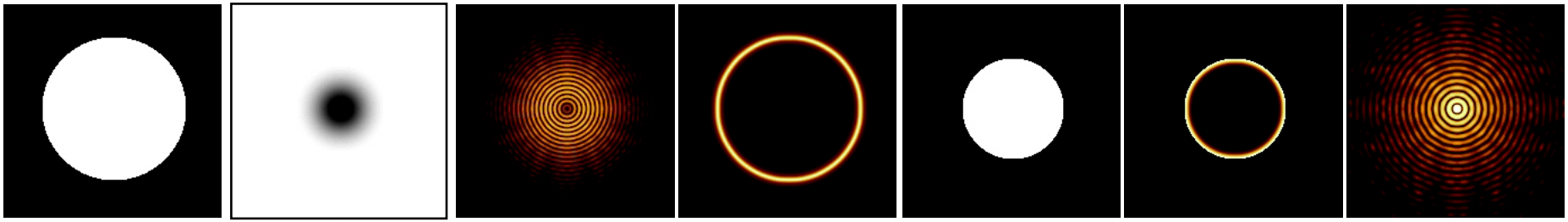


R.G. Lyon
02/25/04

Lyot Coronagraphy

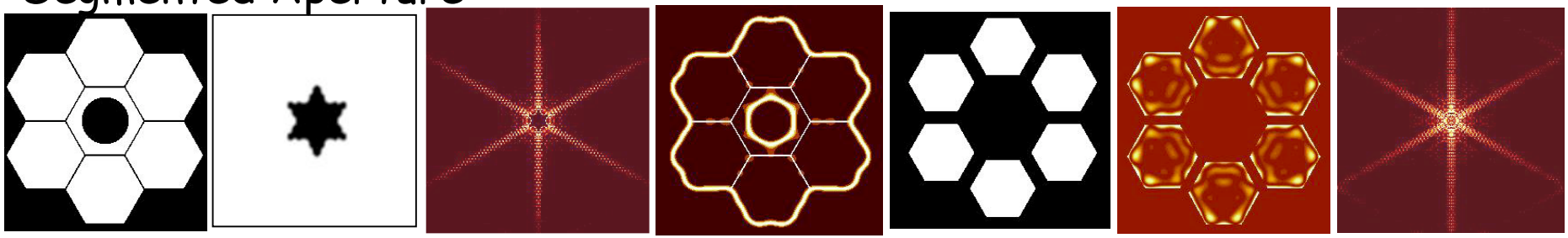


Filled Aperture



Pupil | Occulter | Occulted PSF | Pupil Intensity | Lyot Stop | Lyot Intensity | Apodized PSF

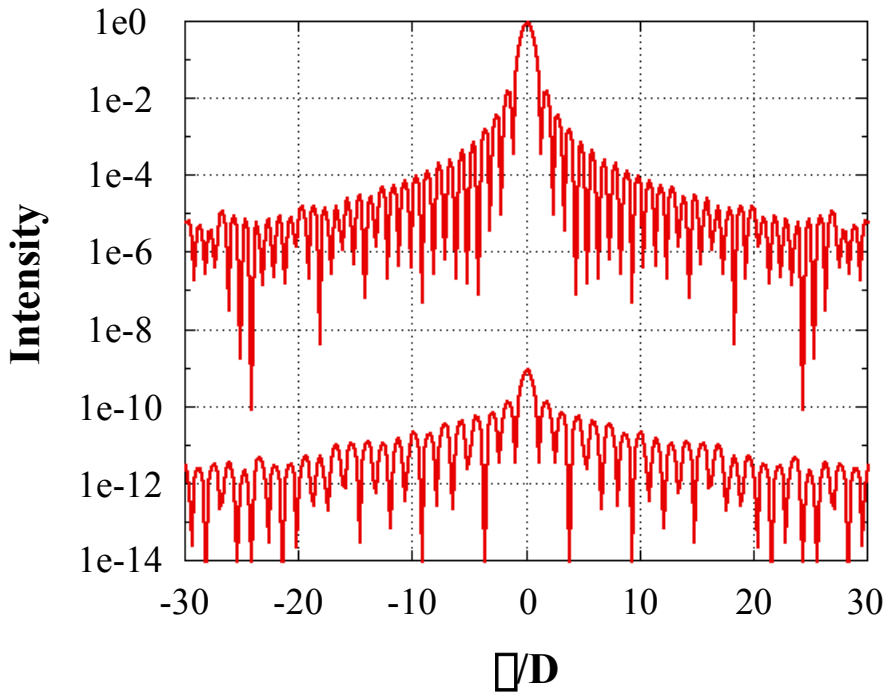
Segmented Aperture



R.G. Lyon
02/25/04

PSF Slices

Soft-Edge Occulting Mask



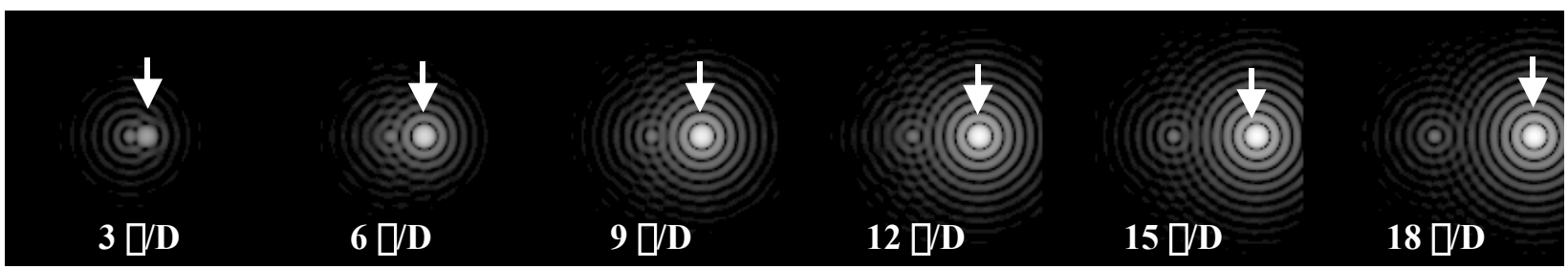
Occulting Mask

$$T(r) = 1.0 \cdot e^{-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2}$$

$$\sigma = 4\ \lambda/D$$

Planet/Star at 1e-6 Luminosity Ratio at 75% Lyot Stop

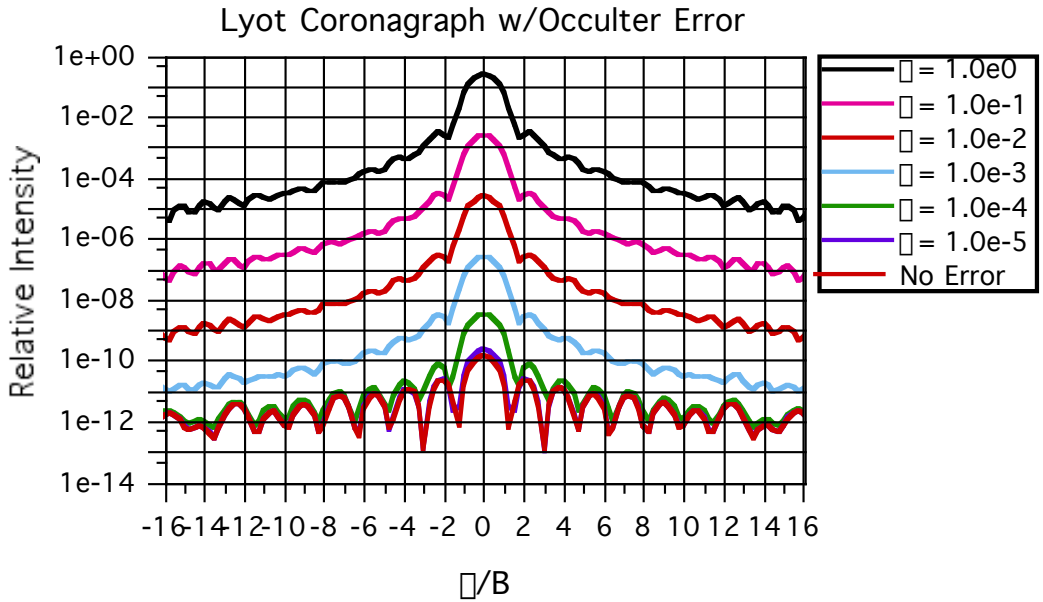
- **Soft-edge ring occulting mask, sigma = 4.0 λ/D**
- **75% Lyot Stop**
- **1e-6 Luminosity Ratio**
- **Monochromatic**
- **plots are log-stretched, arrow points to planet.**

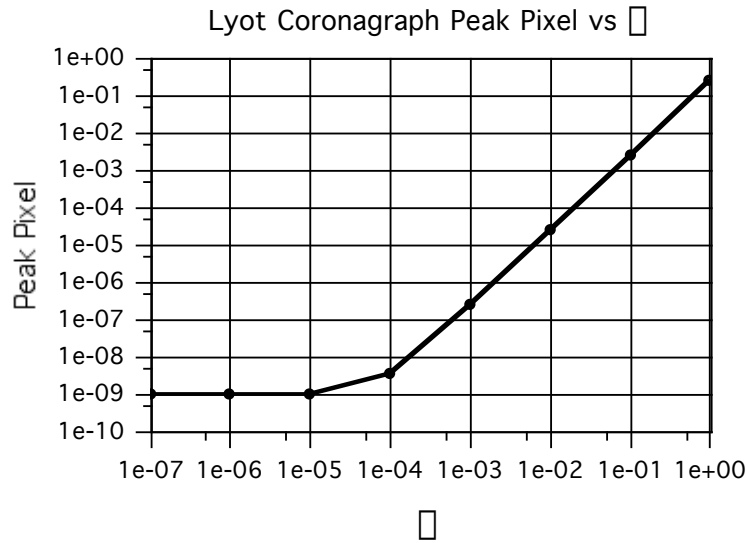


R.G. Lyon
02/25/04

Soft-Edge Lyot PSF w/Opacity Error

"Leakage"





Soft-Edge Lyot on-axis PSFs w/Opacity Error

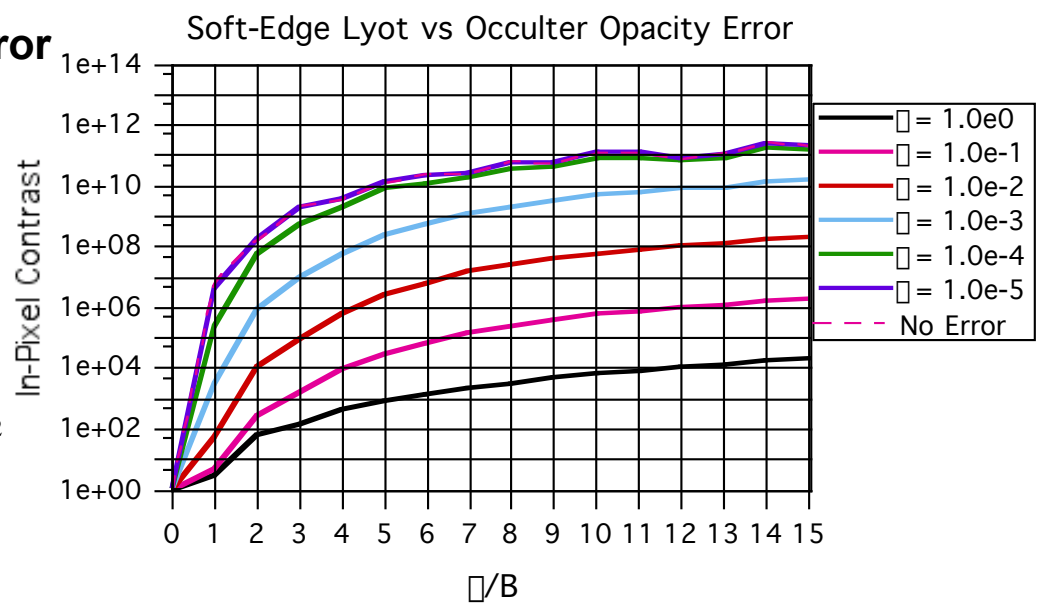
Polychromatic 0.5 - 0.7 microns

70% Lyot stop

The transmission of the occulter is given by:

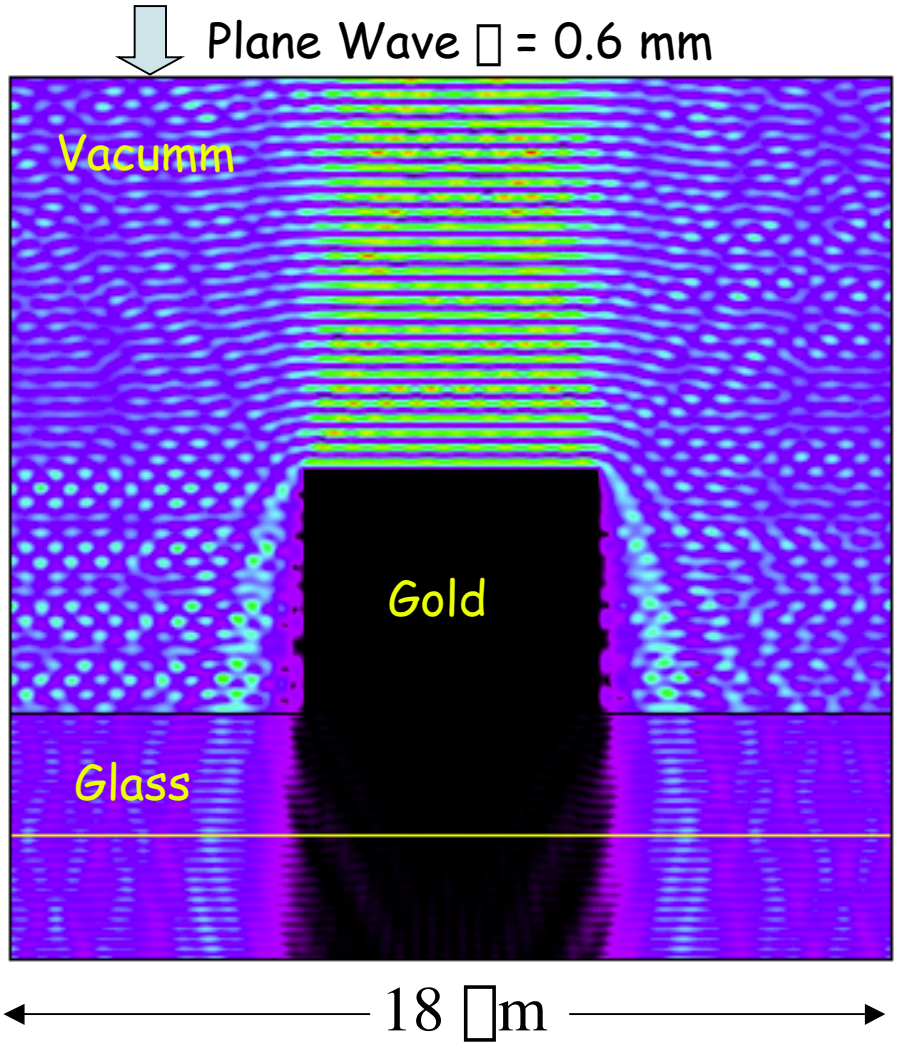
$$T(r) = 1 - (1 - \alpha)e^{-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2}$$

Thus α is ***amplitude opacity***, intensity opacity is ~ α^2

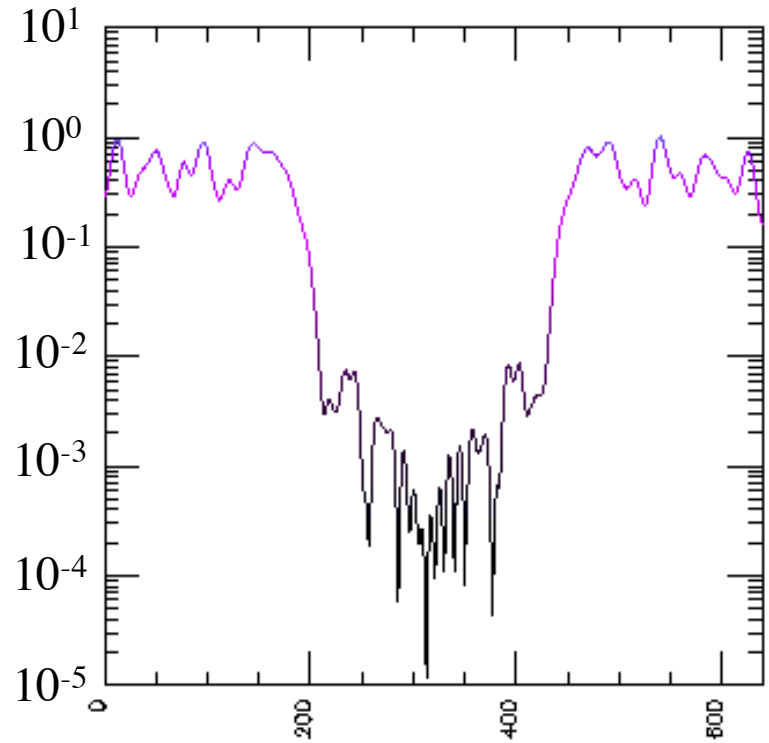


R.G. Lyon
02/25/04

Occulter Leakage
(Ron Shiri's VOM)

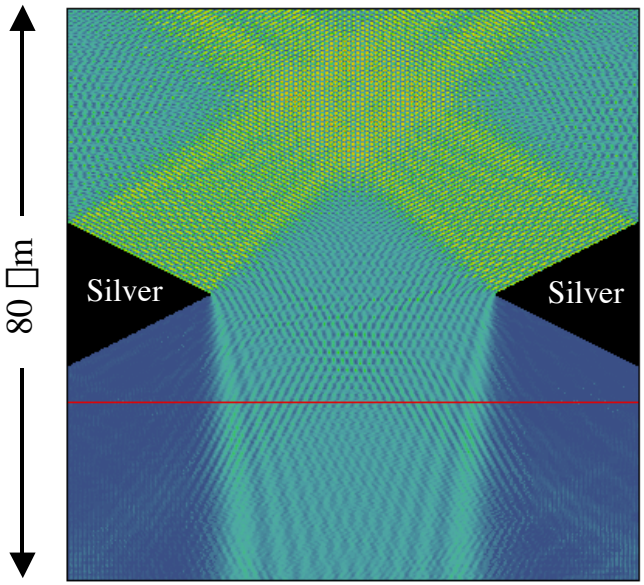


□ = 0.6 □m, 6 □m of Gold thick
on 5 □m of glass, 18 x 18 um box

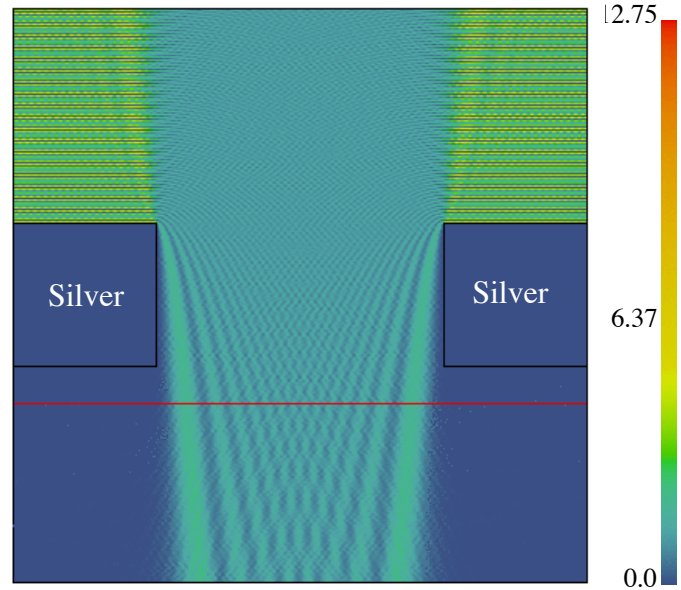


R.G. Lyon
02/25/04

Aperture Edge Effects
(Ron Shiri's VOM)



EM FEM Solution, = 1 micron
20 m thick Silver Bevelled Edge Aperture



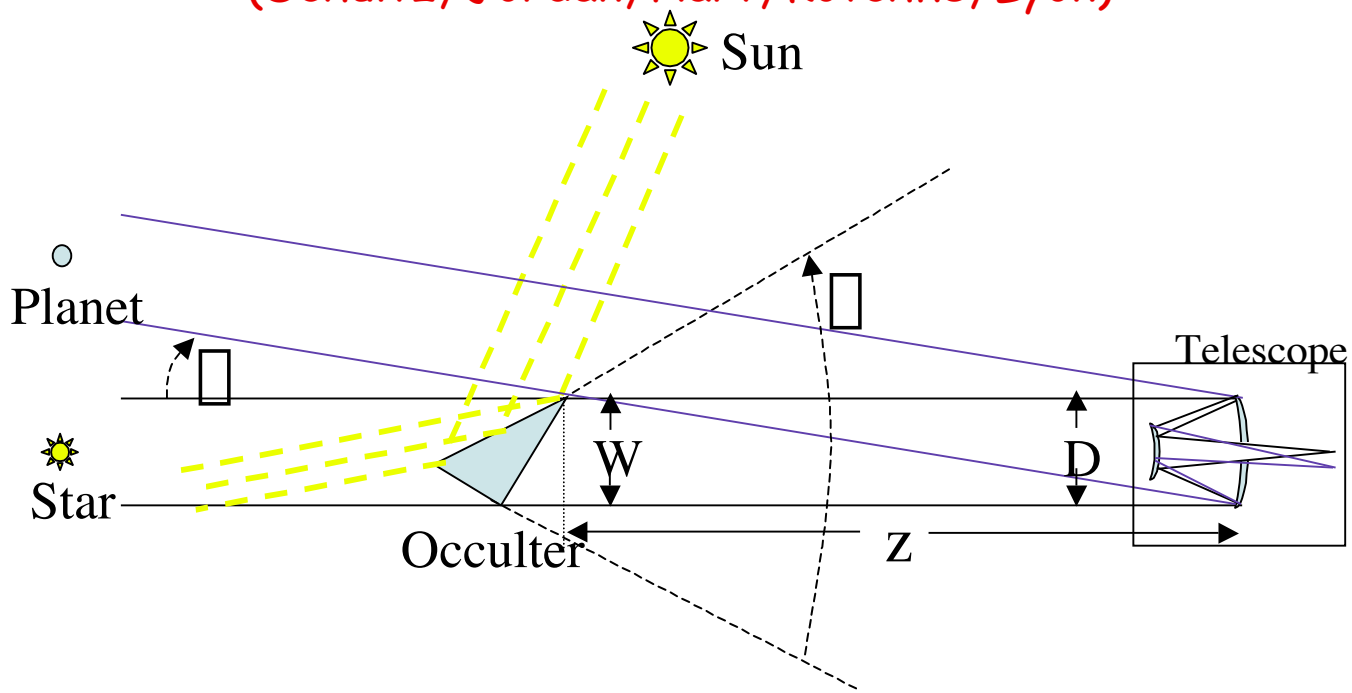
EM FEM Solution, = 1 micron
20 m thick Silver Square Edge Aperture

- Have to be careful in how edges are made
- Can model diffraction, skin effects, evanescent modes
- Bevelled edges can give wide angle scatter

R.G. Lyon
02/25/04

External Occulters

(Schultz, Jordan, Hart, Kotchke, Lyon)



- External Occulter Acts like Internal Occulter
- De-sensitizes wrt WFE (□/100 rms), Amp Errors, scatter
  - Light never enters the telescope !
- Any Coronagraphic approach can be improved
- Disadvantages
  - Multiple S/C in formation, re-configuration times
  - Use multiple occulters ?

UMBRAS

Umbral
Missions
Blocking
Radiating
Astronomical
Sources

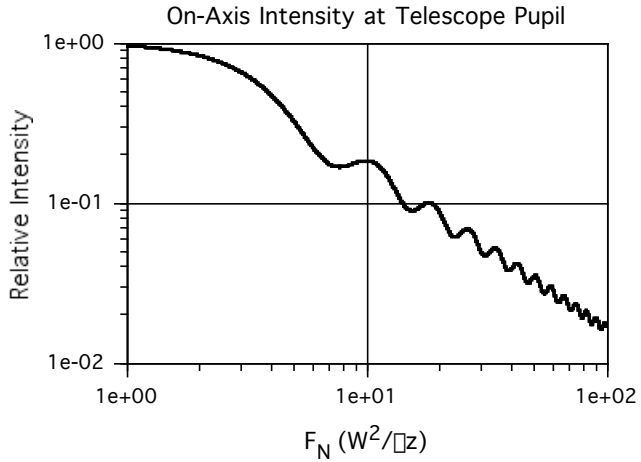
- Opaque or Apodizing
- Self-shading or shack-shade
- Conservative design studies.
- Operations analysis

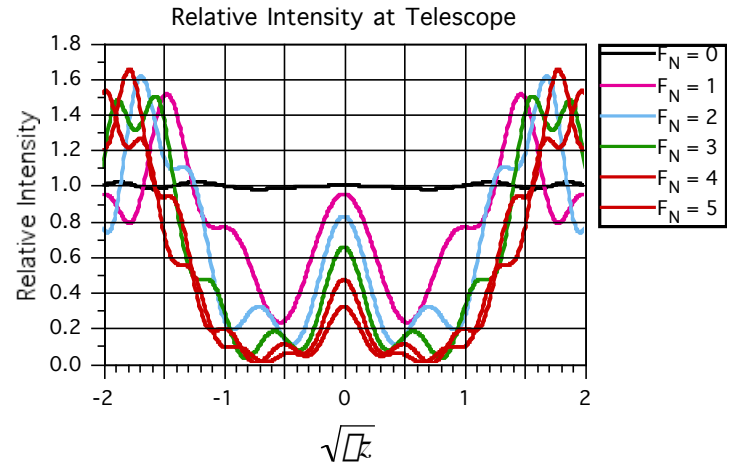
Alfred Schultz, et. al.,
Computer Sciences Corp.,
1998+

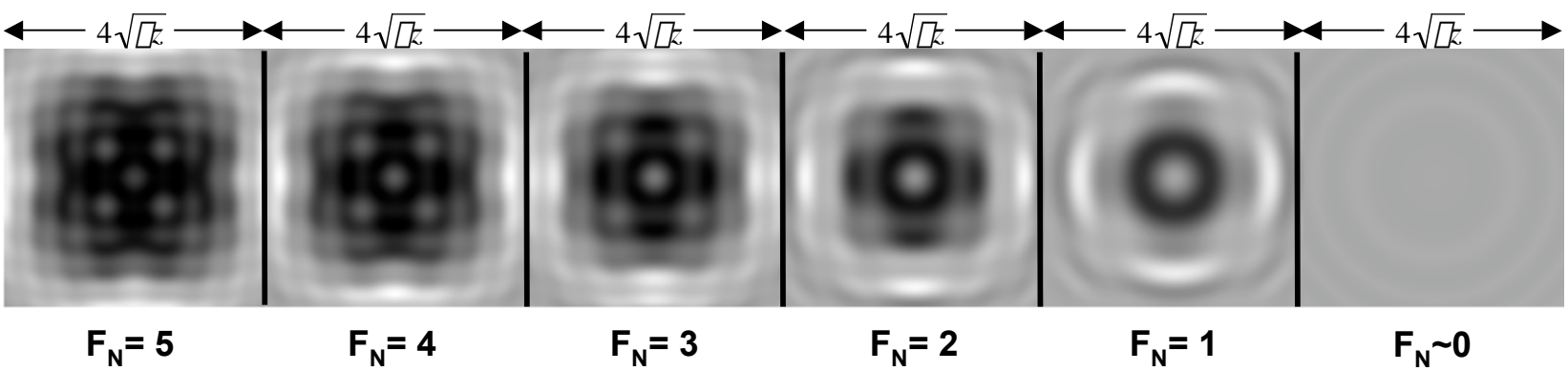
External Occulters

Propagation to Telescope Aperture

R.G. Lyon
02/25/04

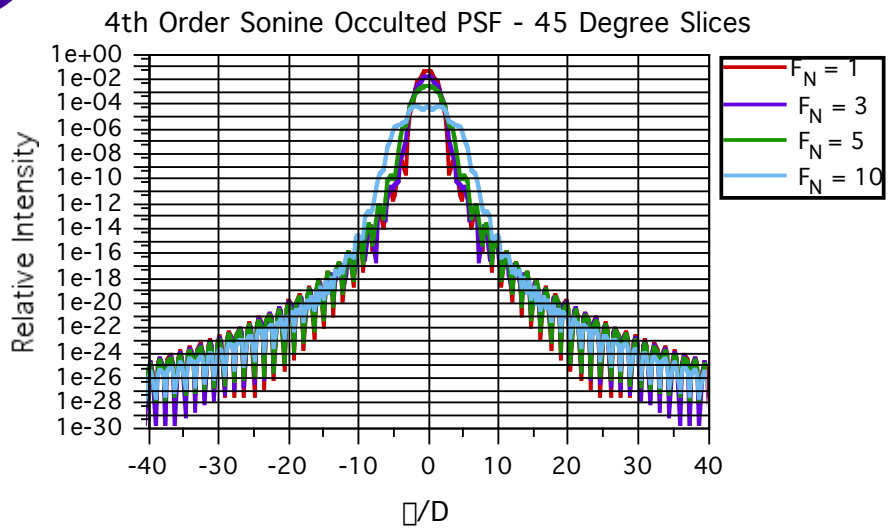


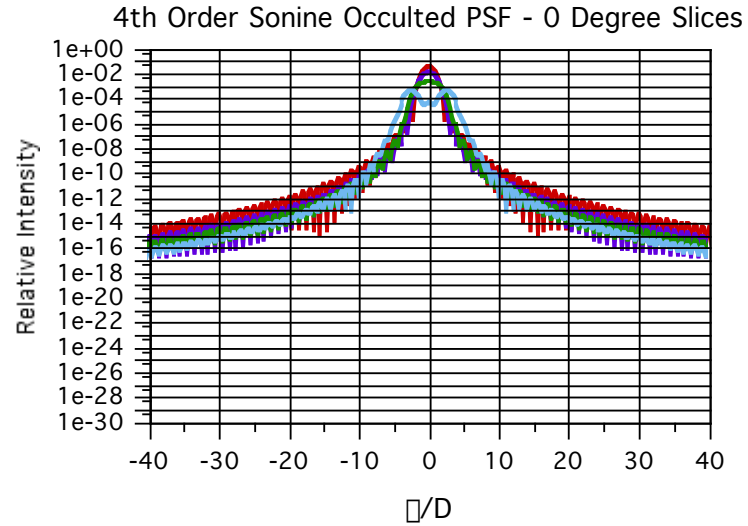




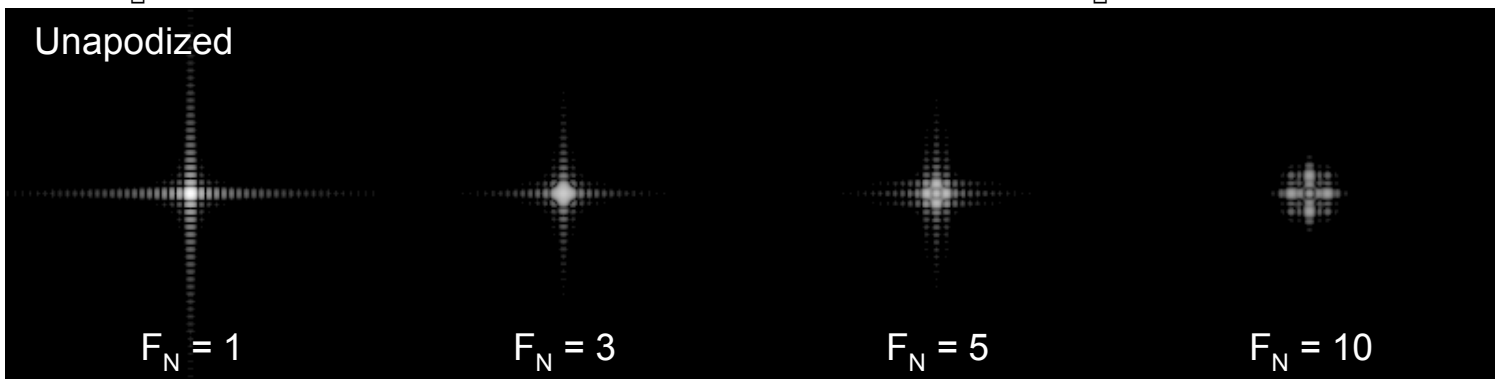
External Occulter PSFs

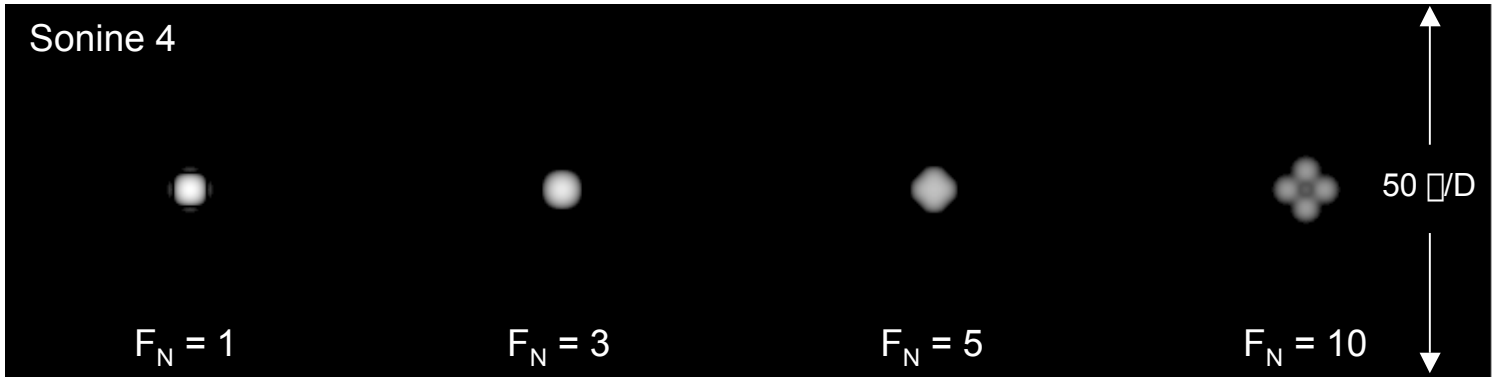
R.G. Lyon
02/25/04





Square Occulter
Square Telescope
Sonine 4 Apodization
= D/W = 0.5
Monochromatic

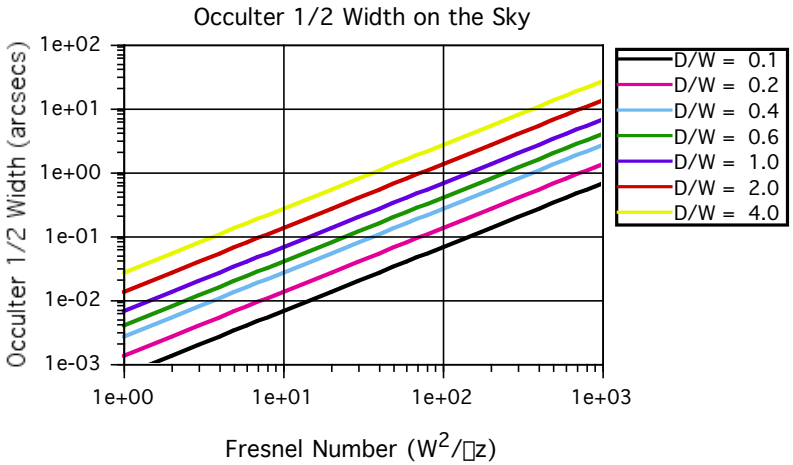


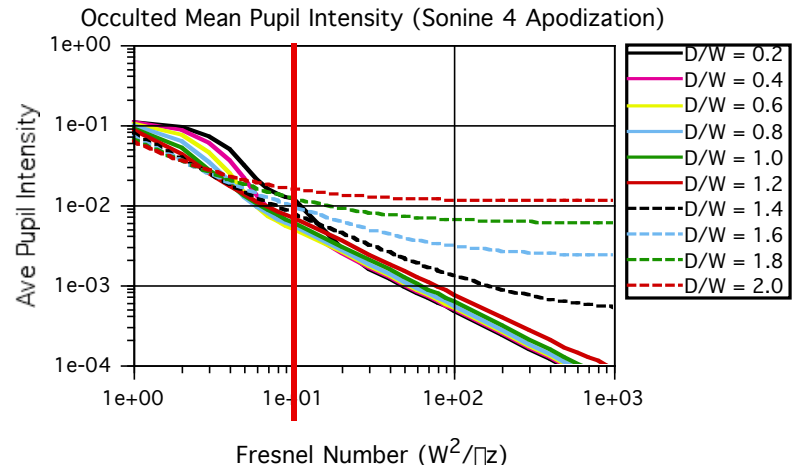


R.G. Lyon
02/25/04

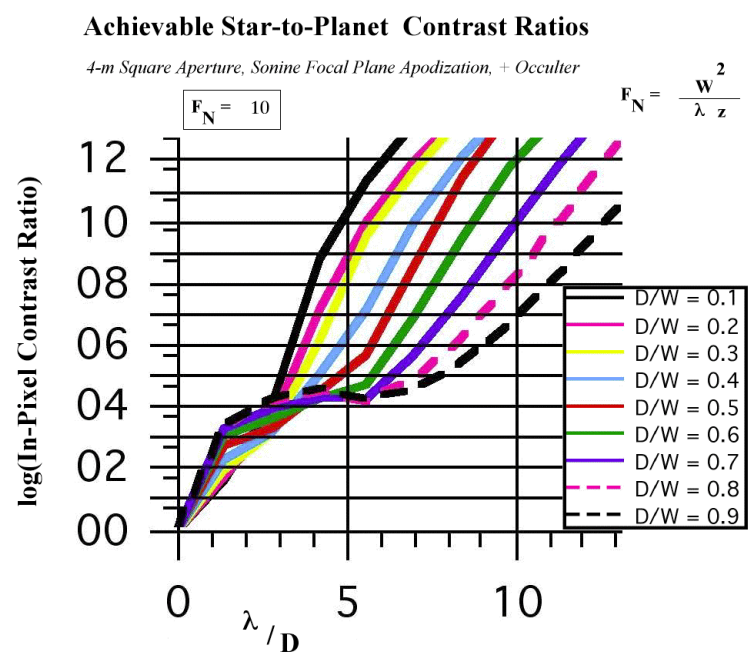
External Occulters

Occulter Effectiveness





- Fresnel numbers > 10 => 1% stellar light enters telescope
- Reduces WF reqmt's by ~100 !
- Achieves Jupiter contrasts 3 □/D
- Earth contrasts @ 5 □/D

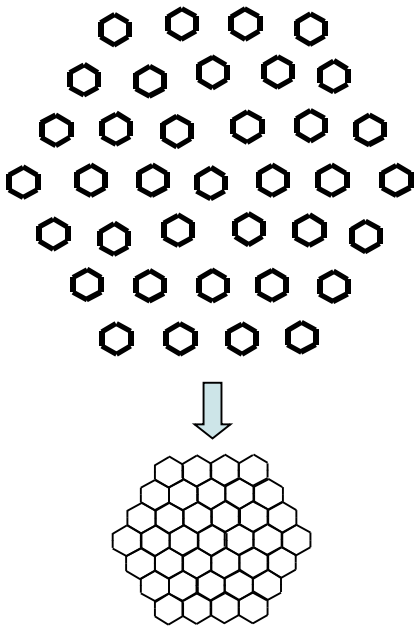


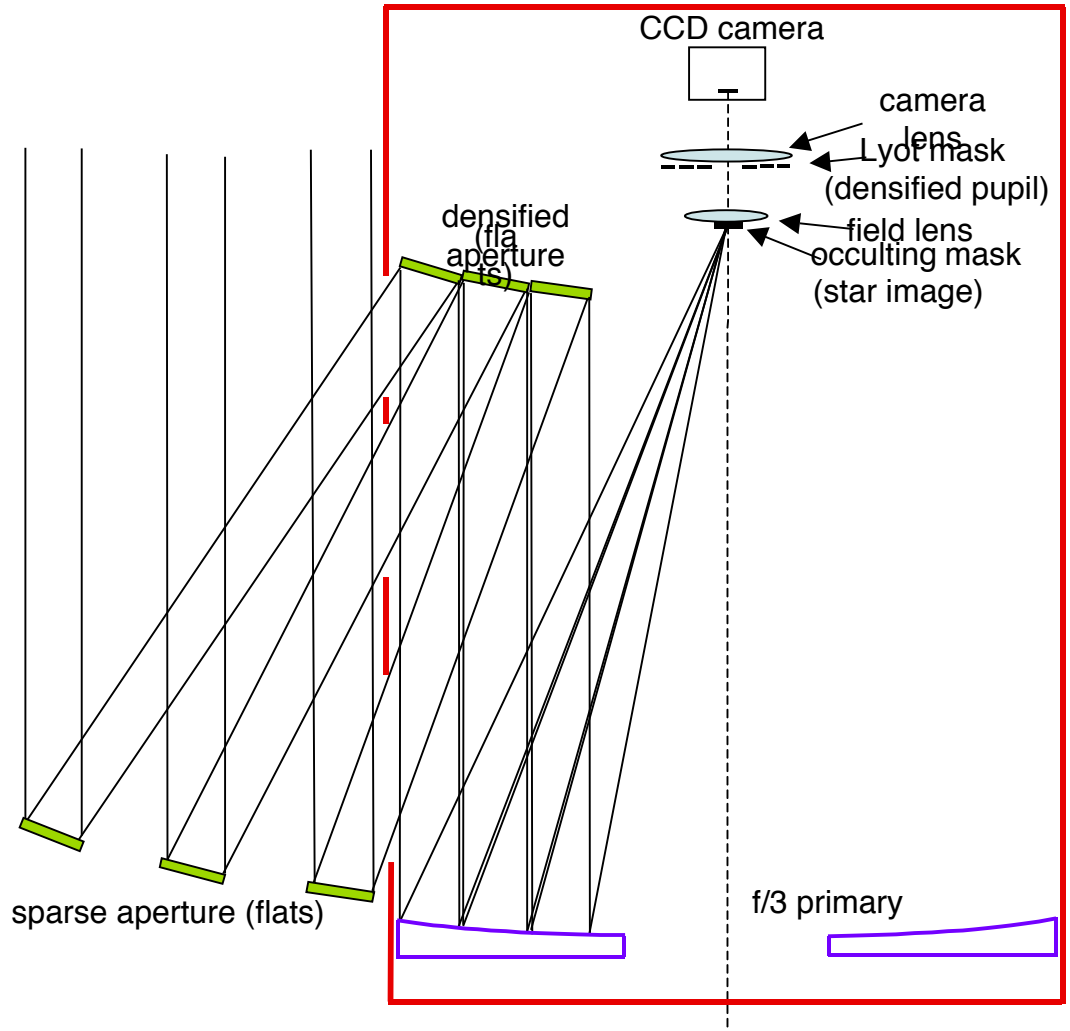
http://www.umbras.org

Hypertelescope Coronagraphy

Labeyrie, Gezari, Lyon

R.G. Lyon
02/25/04



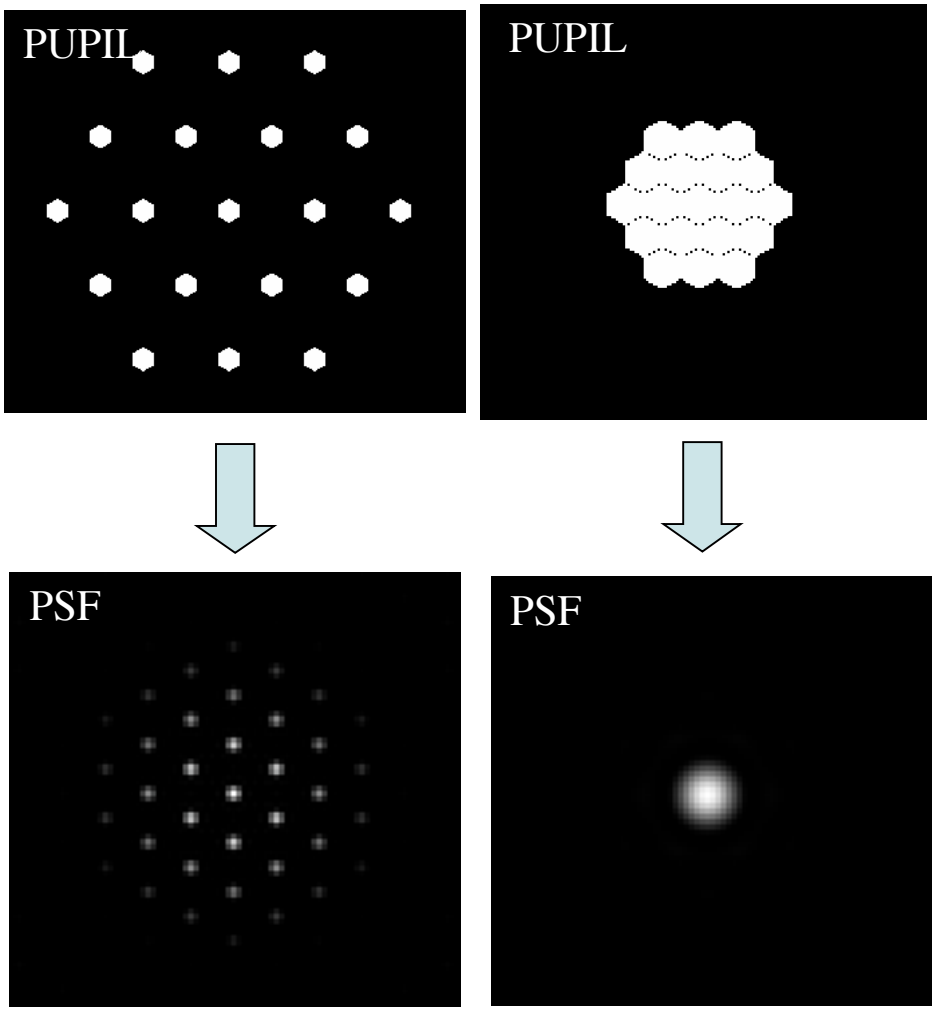


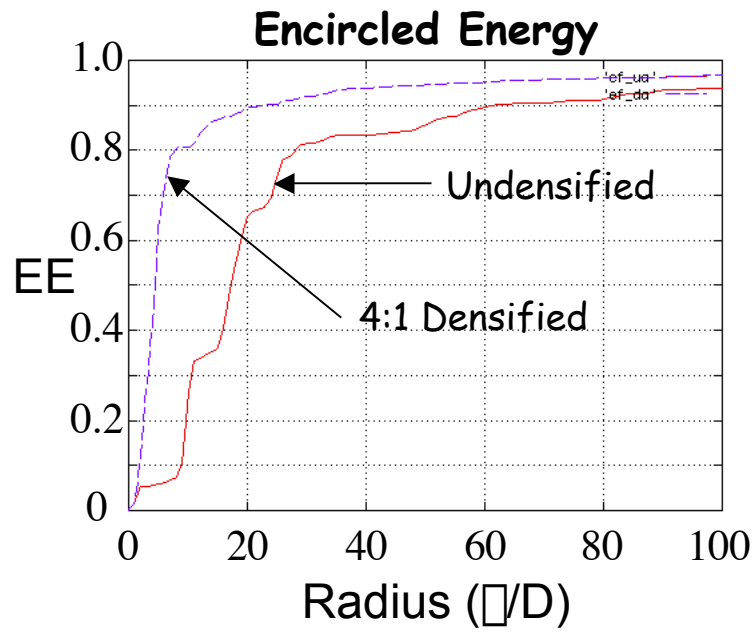
- Densify w/o change the SubAps
- Brighter core, less sidelobes
- Same aperture area
- PSF is space variant
- Useful for small FOV => Coronagraph ?

R.G. Lyon
02/25/04

Hypertelescope

4:1 Pupil Densification





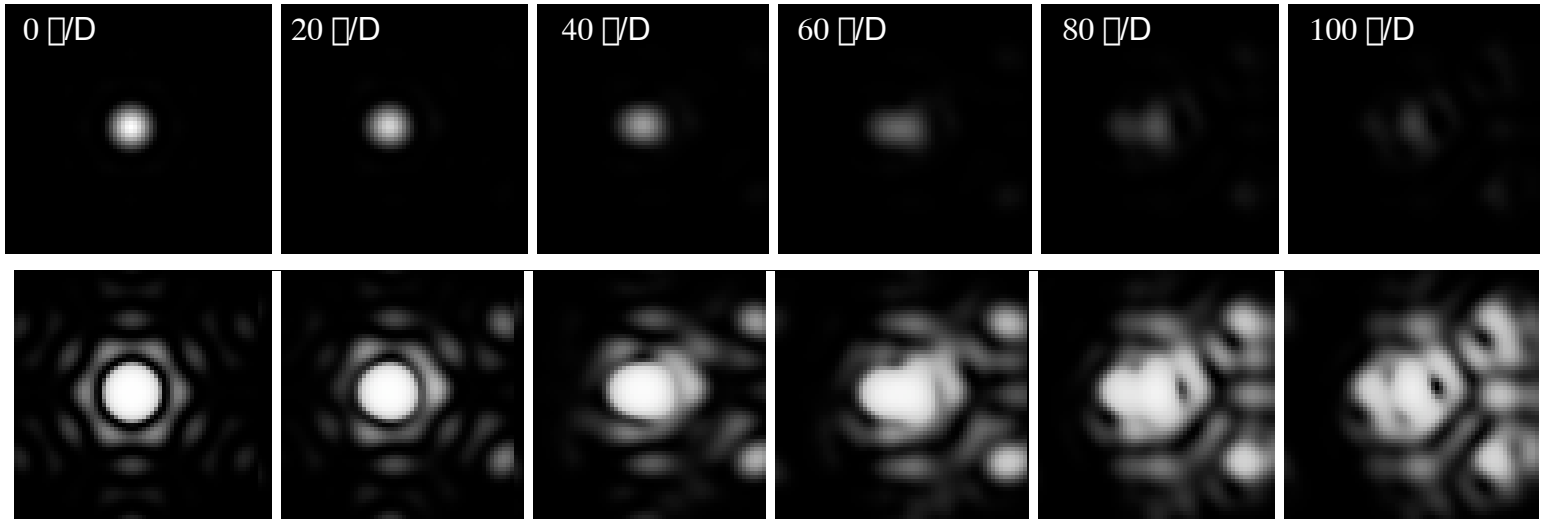
- 19 Sub-apertures in Hex pattern
- 4:1 densification
- More energy packed in core
- EE is signficantly higher
- Much higher on-axis sensitivity
- Will degrade rapidly with FOV

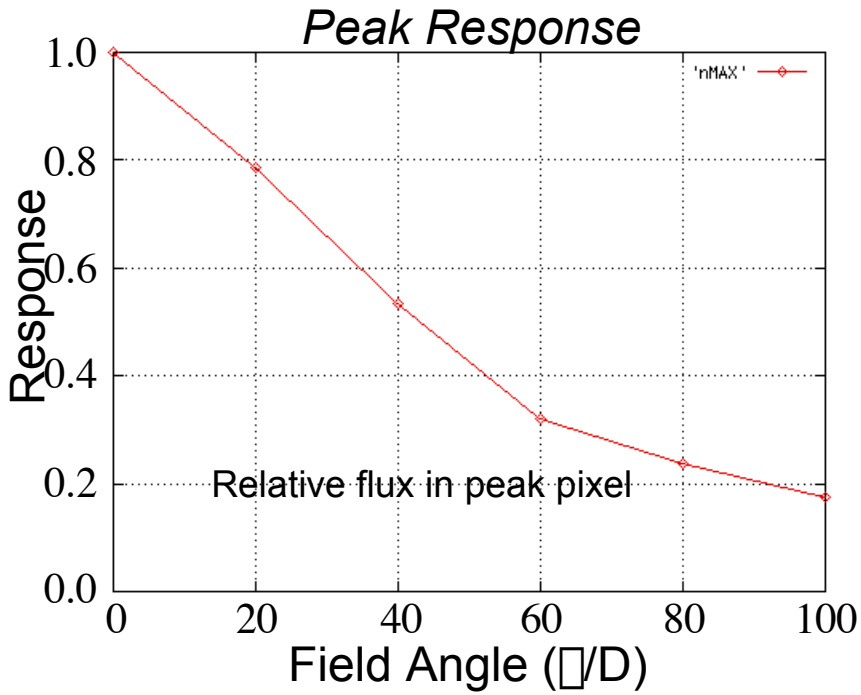
R.G. Lyon
02/25/04

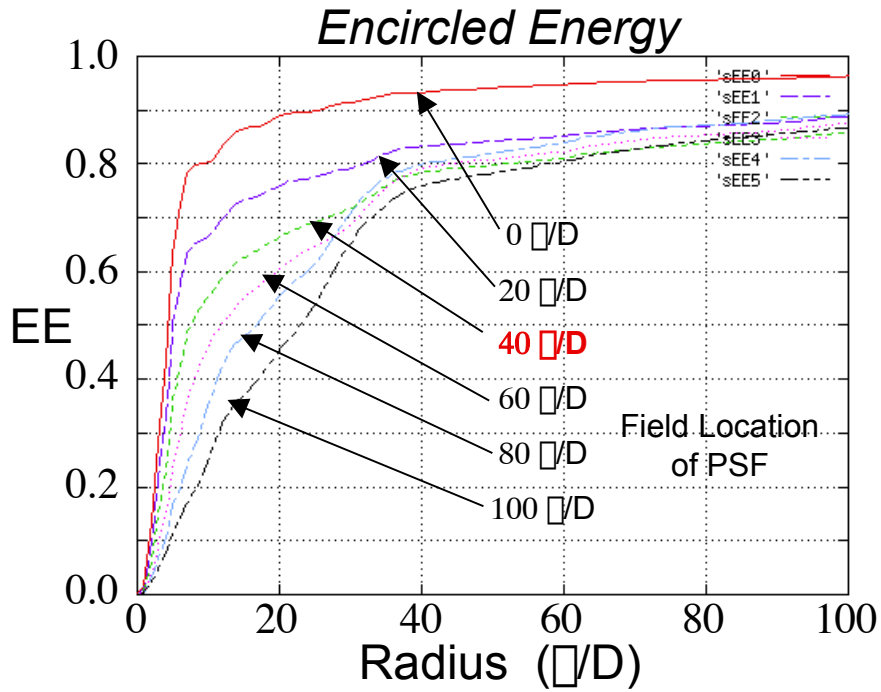
Hypertelescope PSFs vs FOV

Linear Scale

Log Scale

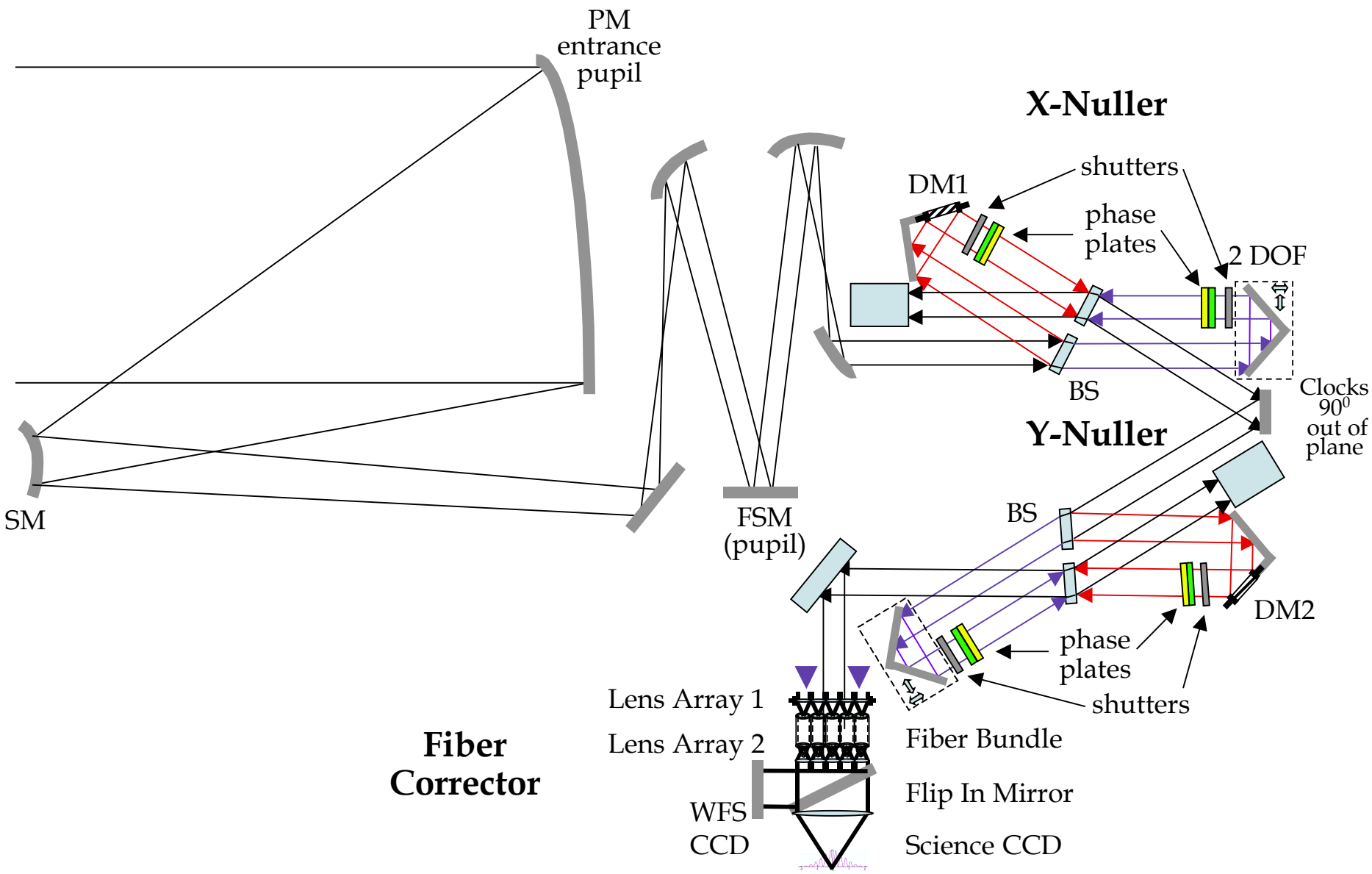






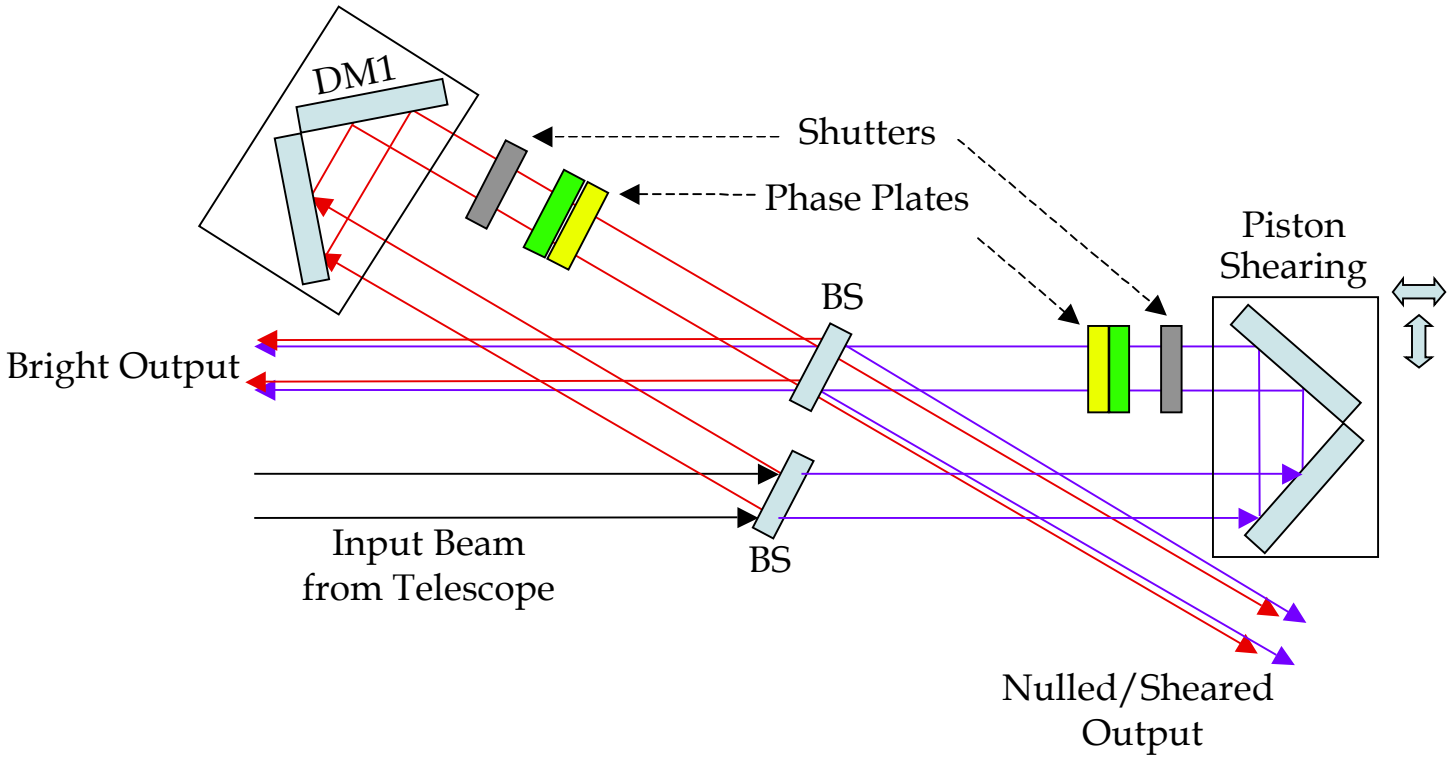
R.G. Lyon
02/09/04

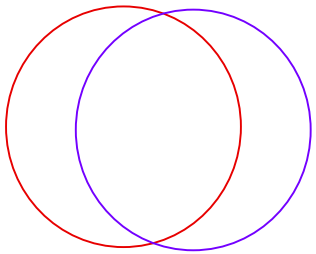
Shao Nuller Concept



R.G. Lyon
02/01/04

X-Direction Nuller



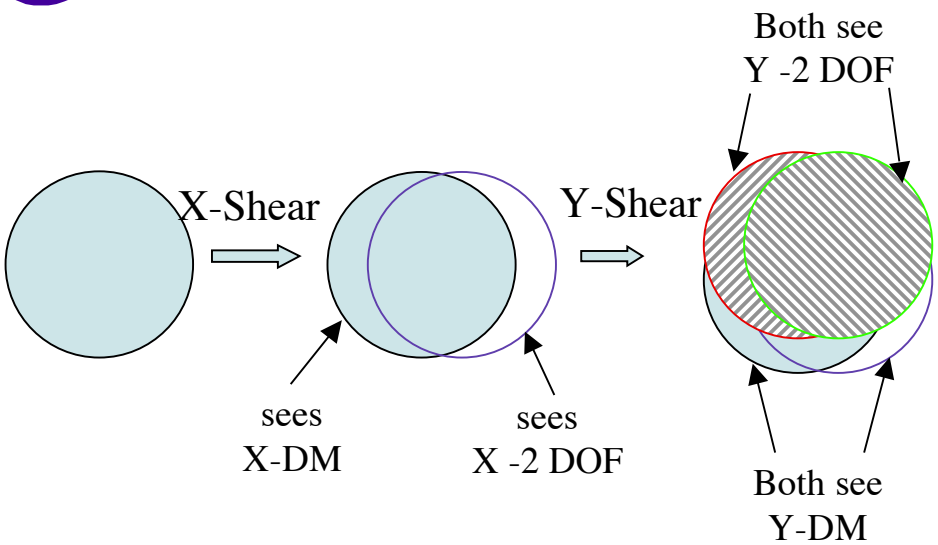


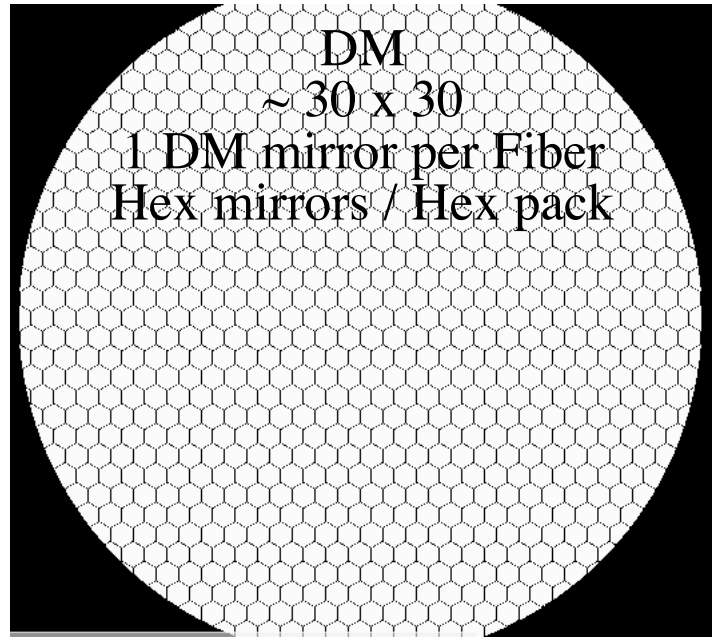
Sheared
Pupils

- Telescope pupil imaged at DM1
- DM1 pitch matched to Fiber Bundle
- DM1 orientation matched to Fiber Bundle
- DM1 corrects only one beam to match other
- Phase plates put in achromatic π-phase shift
- Shutters used for metrology to drive DM1
- Bright output used for FSM and Metrology
- Nulled output nulled in overlap pupil via DM1

R.G. Lyon
02/19/04

Overlap Pupil & Shearing





$$I(\theta_x,\theta_y) = \sin^2\left[2\pi s_x \frac{D}{\lambda}\theta_{x0}\right]\sin^2\left[2\pi s_y \frac{D}{\lambda}\theta_{y0}\right] PSF(\theta_x - \theta_{x0}, \theta_y - \theta_{y0})$$

IWD => $\sin^2\left[2\pi s_x \frac{D}{\lambda}\theta_x\right] = 1$ or $\theta_{IWD} = \frac{1}{4s}\frac{\lambda}{D}$

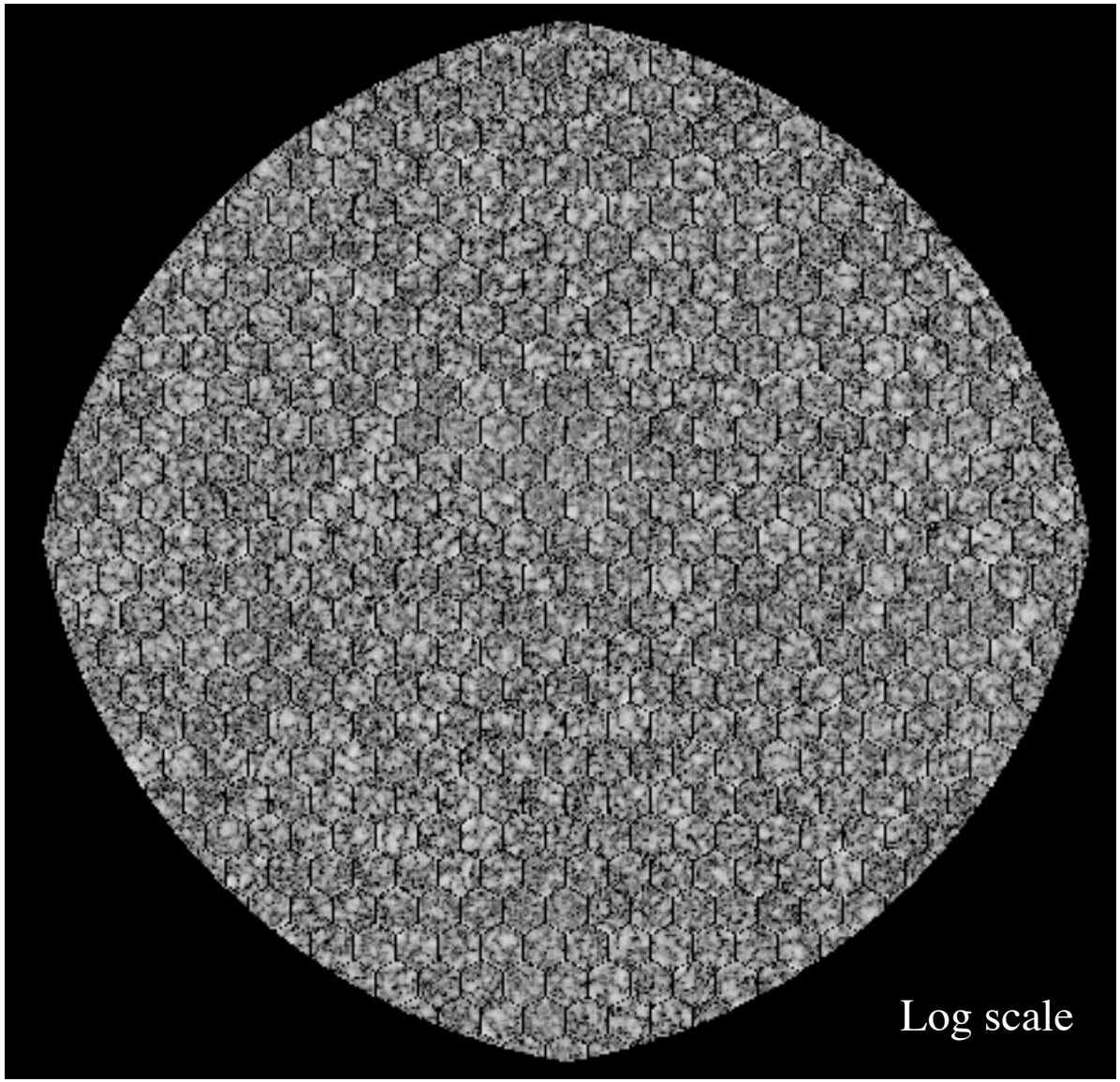
and "s" in units of fractional pupil

- Shear of 16.67% gives 3 l/D IWD
- IWD @ 1st transmission peak
- 30 DM elements:
  - shear 5 DM's EW
  - shear 3 DM's NS
- Gives minimal diffraction effects
- Vari-Shear in integral DM units

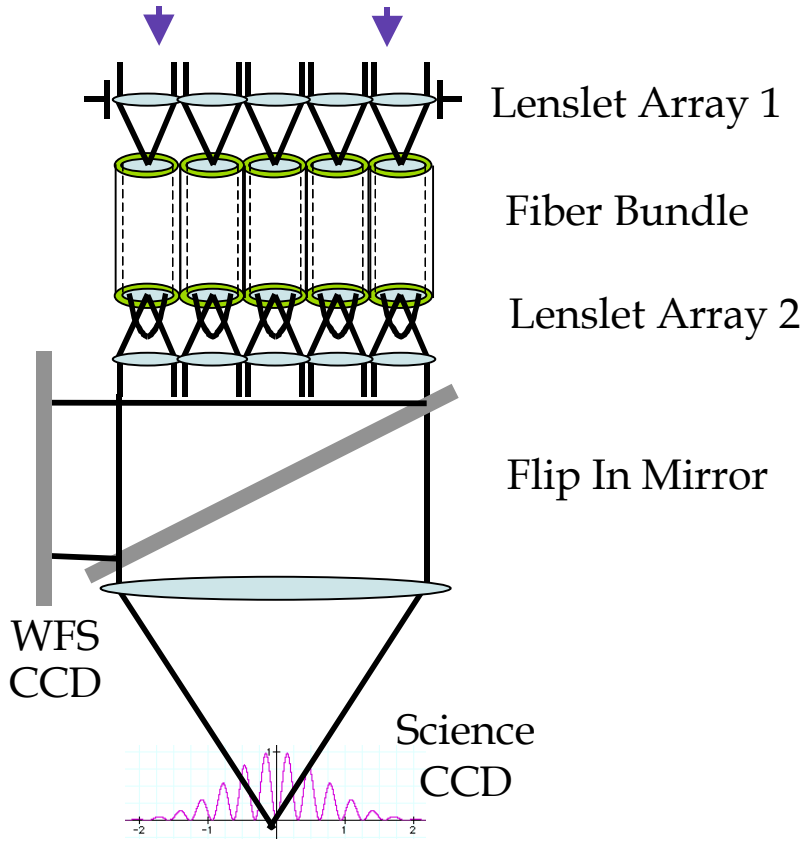
R.G. Lyon
02/19/04

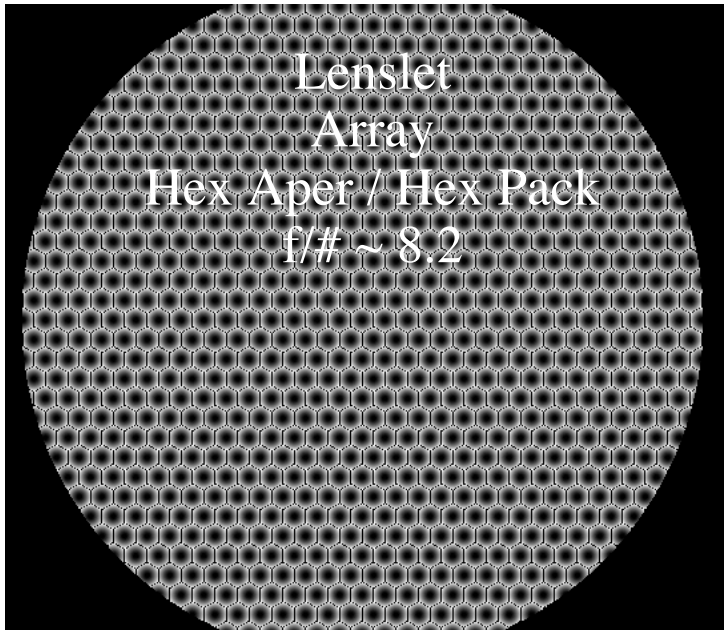
Overlap Pupil & Shearing

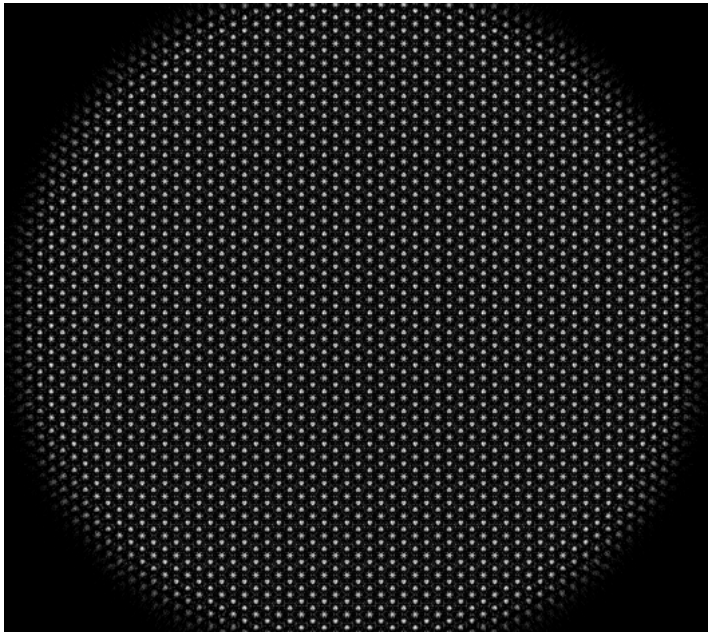
Pupil Intensity @ lenslet array
DM gaps are overlaid
16.67 % Shear X and Y



Fiber Corrector



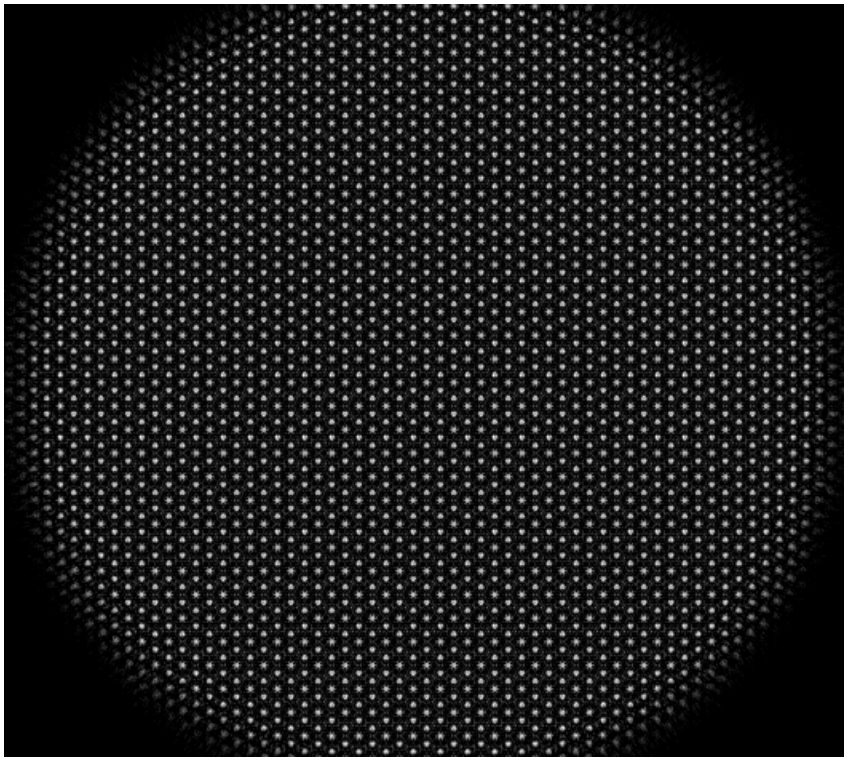




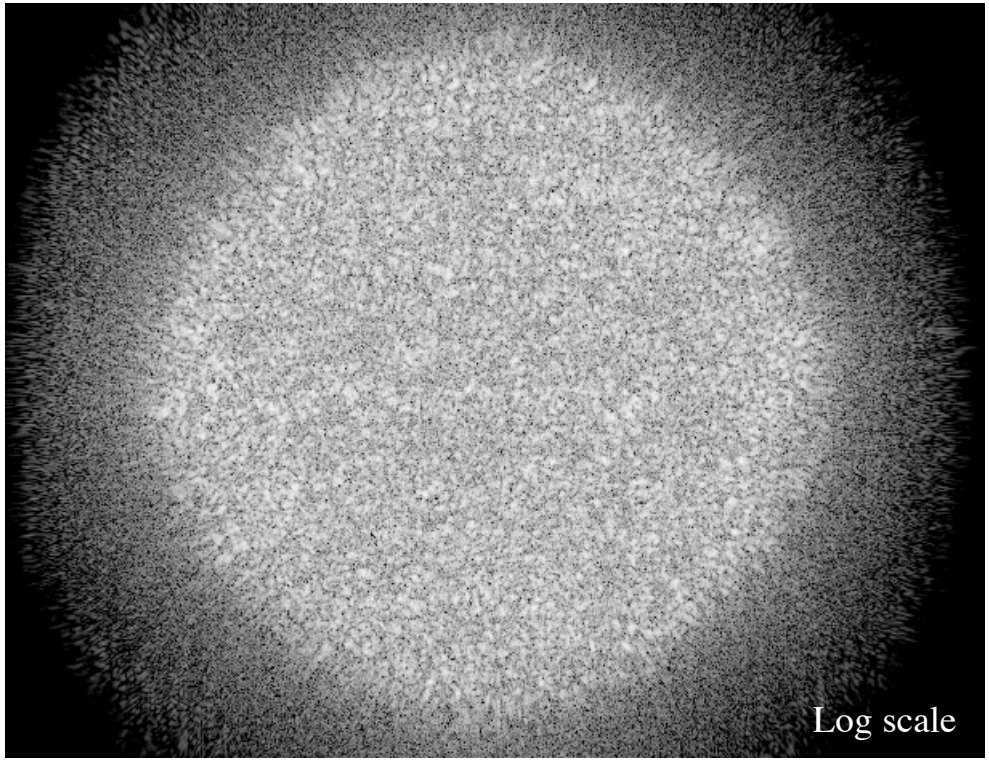
Spot Pattern on fibers w/o nulling
Each PSF core ~ 12 μm
Matched to fiber core ~ 12 μm
Cladding ~ 125 μm diameter

R.G. Lyon
02/19/04

After Lenslet Array
At Entrance of Fiber Bundle



Intensity @ Fibers
Un-nulled no WFE



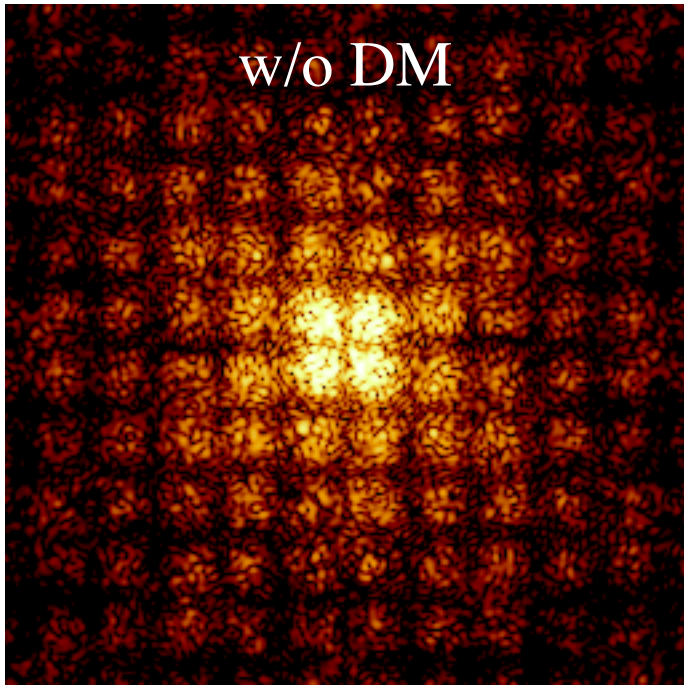
Intensity @ Fibers
Nulled w/ WFE

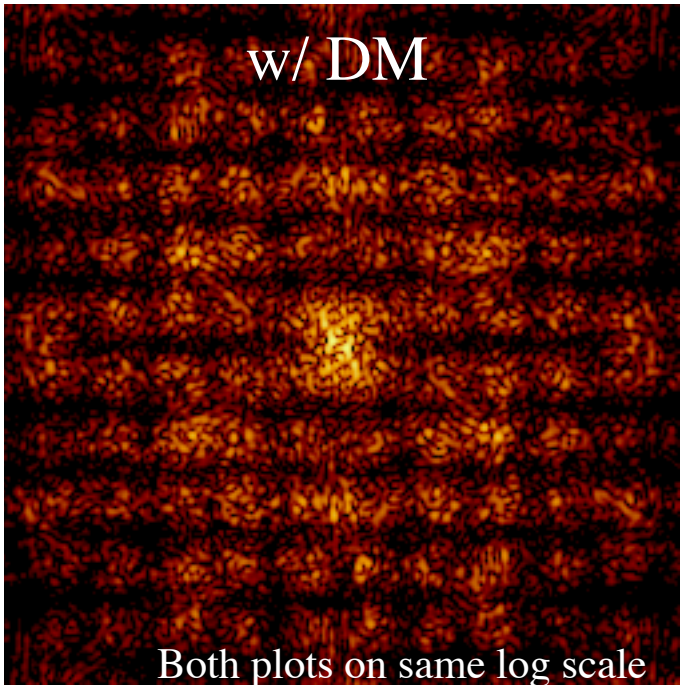
R.G. Lyon
02/16/04

Wavefront Error Induces Null Leakage

with and w/o DM & without Fiber Corrector

- With and w/o DM
- No fiber corrector

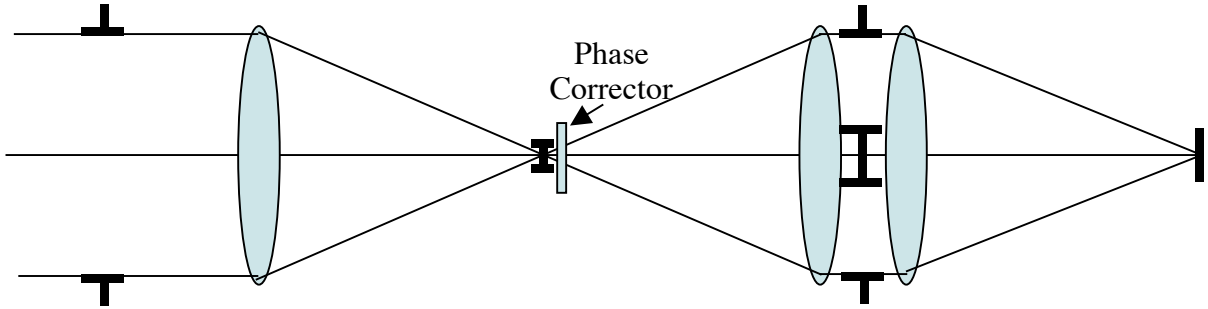




- Speckles Removed by Fiber Corrector
- In principal can achieve 10^{-10} Null !

R.G. Lyon
02/25/04

Labeyrie Corrector

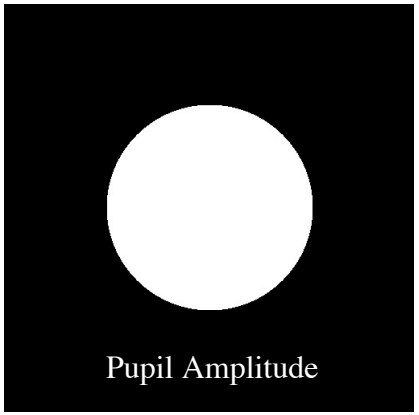


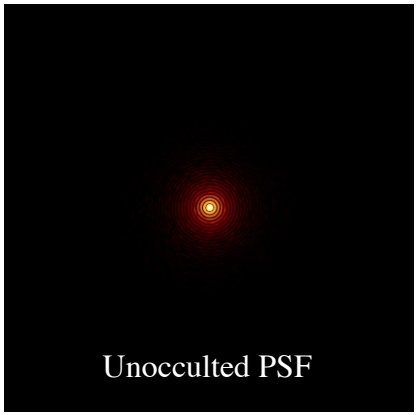
Telescope Exit Pupil
Multi-Stage Entrance Pupil

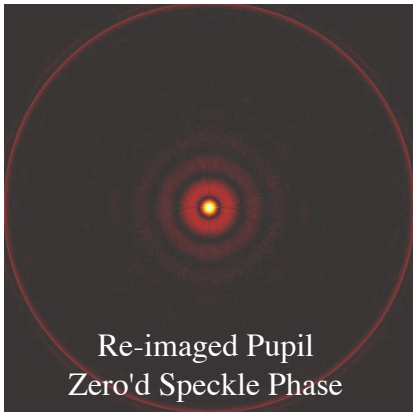
Focal Plane Occulter
Zero'd Speckle Phase

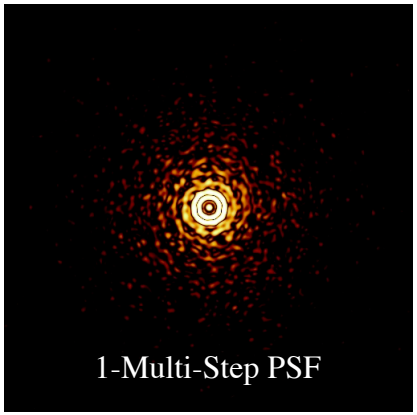
Re-Imaged Pupil
Pupil Occulting Mask

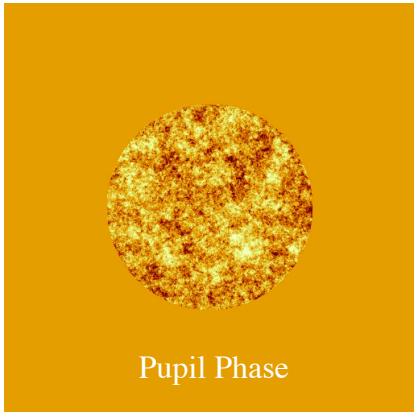
Focal Plane

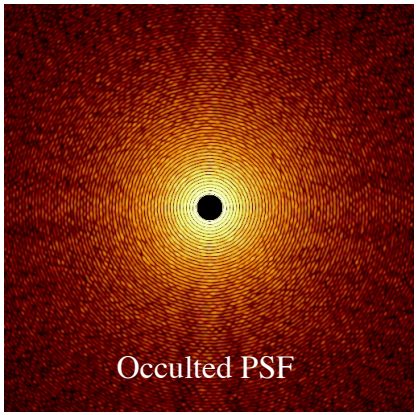

Pupil Amplitude

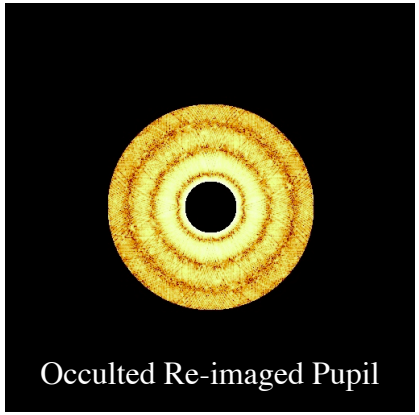

Unocculted PSF


Re-imaged Pupil
Zero'd Speckle Phase


1-Multi-Step PSF


Pupil Phase

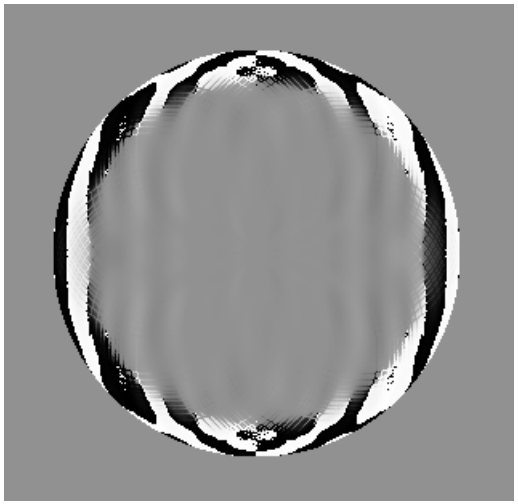

Occulted PSF


Occulted Re-imaged Pupil

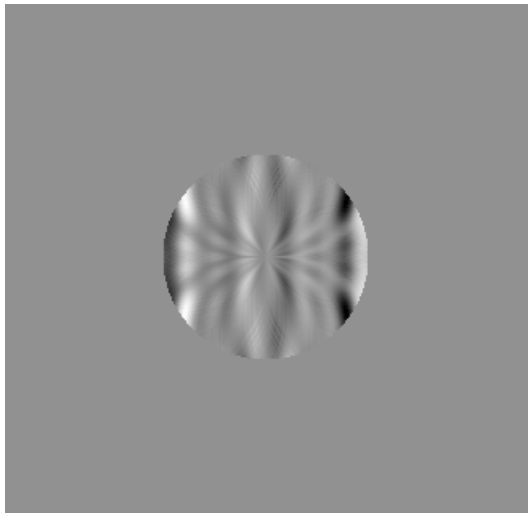
Labeyrie Corrector

R.G. Lyon
02/25/04

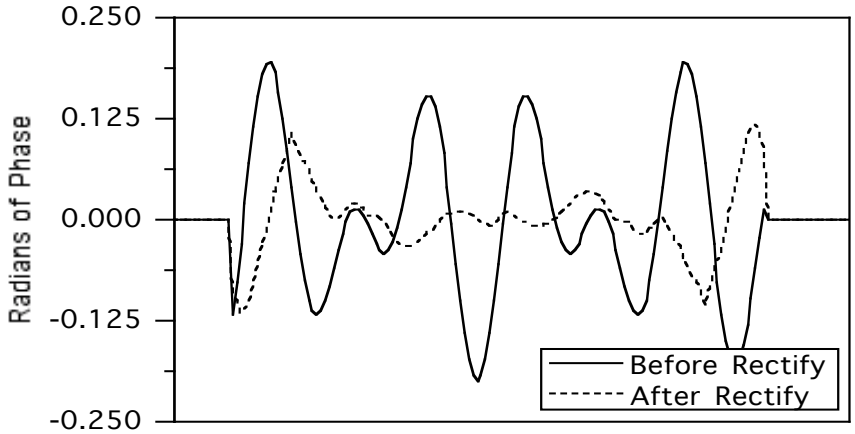
Phase over original pupil
2 low-freq components
□ = 0.0161 □



Phase over 2D reimaged pupil

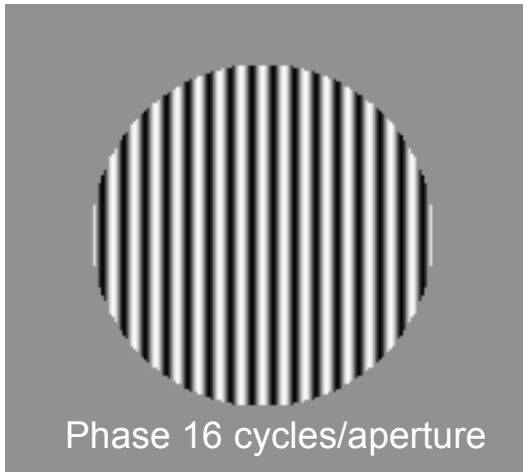


Phase over 2 D reimaged pupil
□ = 0.0085 □

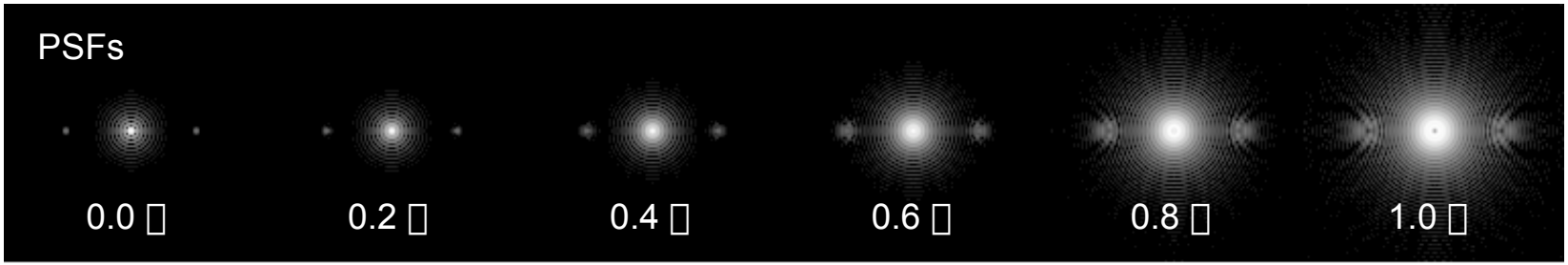


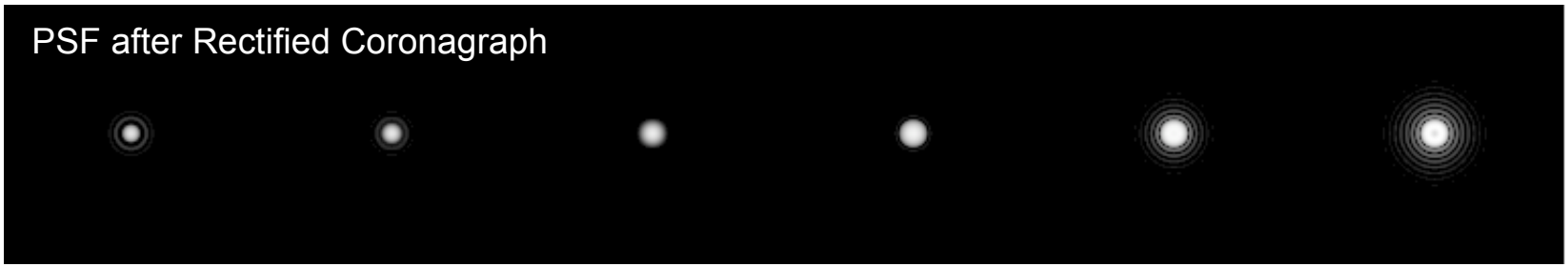
R.G. Lyon
02/25/04

Labeyrie Corrector



0 to 1.0 waves



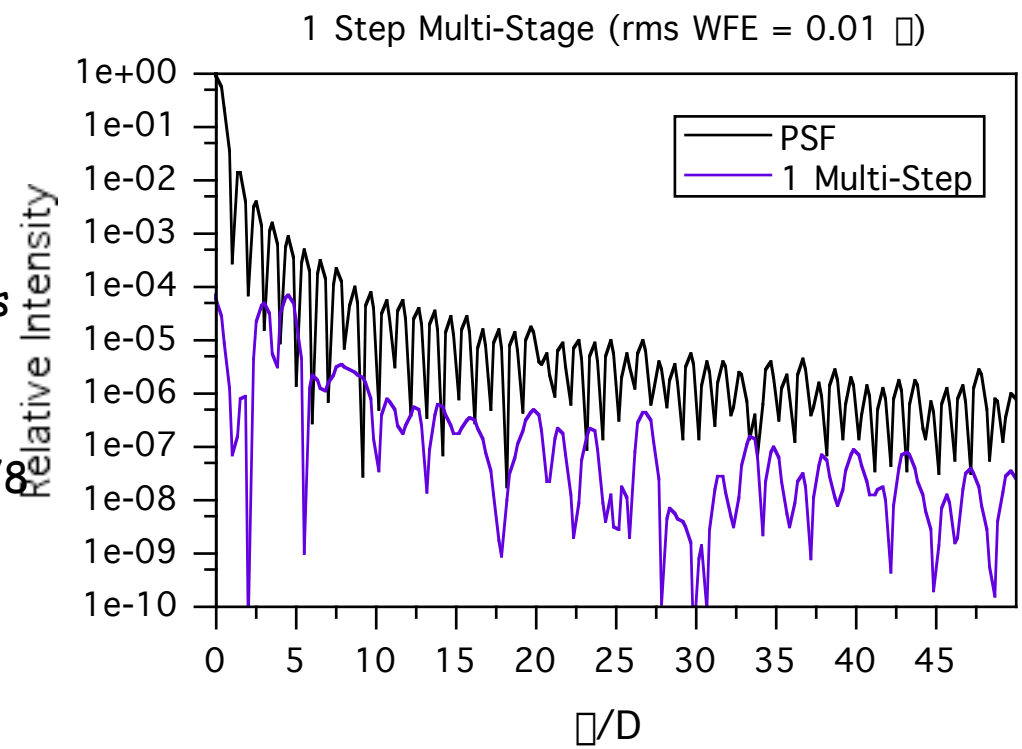


R.G. Lyon
02/25/04

Labeyrie Corrector

Requires:

- Wavefront sensing of speckle phases
- Correction of speckle phases
  need dense DM (or 2 DM method)
- Need to correct speckle phases to $\lambda/8$



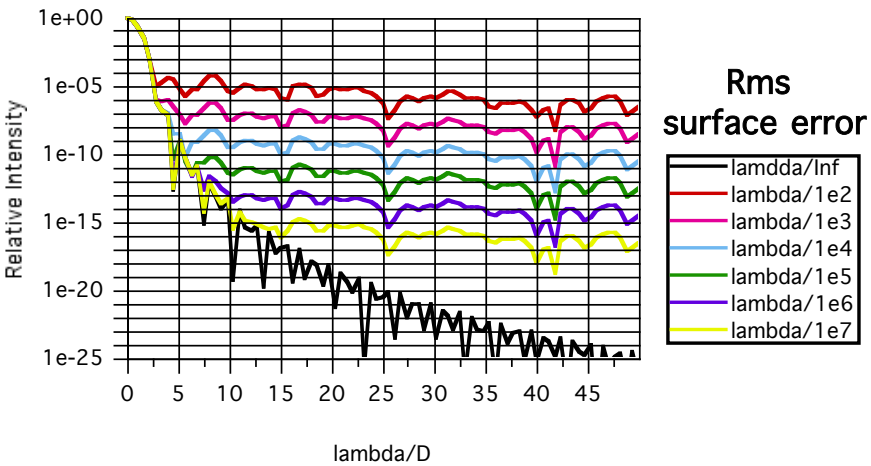
- Lowers WFE 1 order magn per step
- Lowers PSF wings ~2 orders of magnitude
- Increases Contrast ~2 orders of magnitude
- Harvard/CfA/GSFC funded for Tech Demo

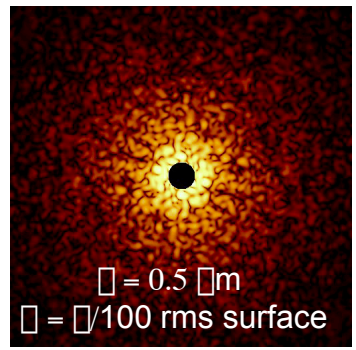
R.G. Lyon
02/25/04

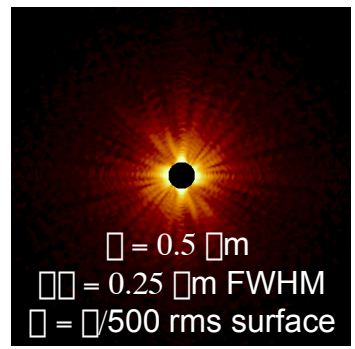
Real World Problems

- Optical Quality => Wavefront and Amplitude

$$PSF(\lambda) = \left[1 - \sigma_A^2\right]\left[1 - k^2\sigma_W^2\right]PSF_0(\lambda) + \sigma_A^2 PSD_A(\lambda) + k^2\sigma_W^2 PSD_W(\lambda)$$

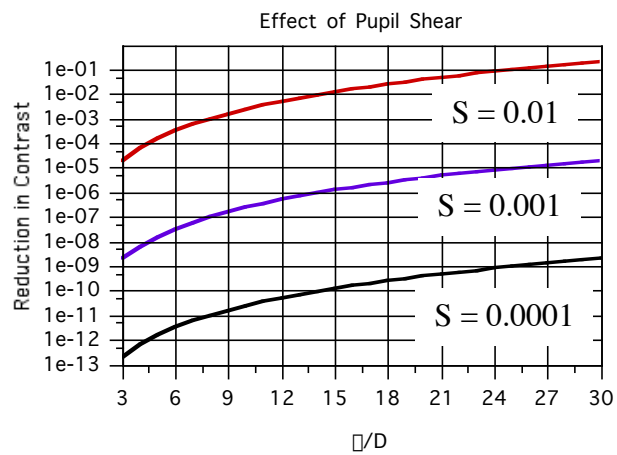






- Pupil Shear

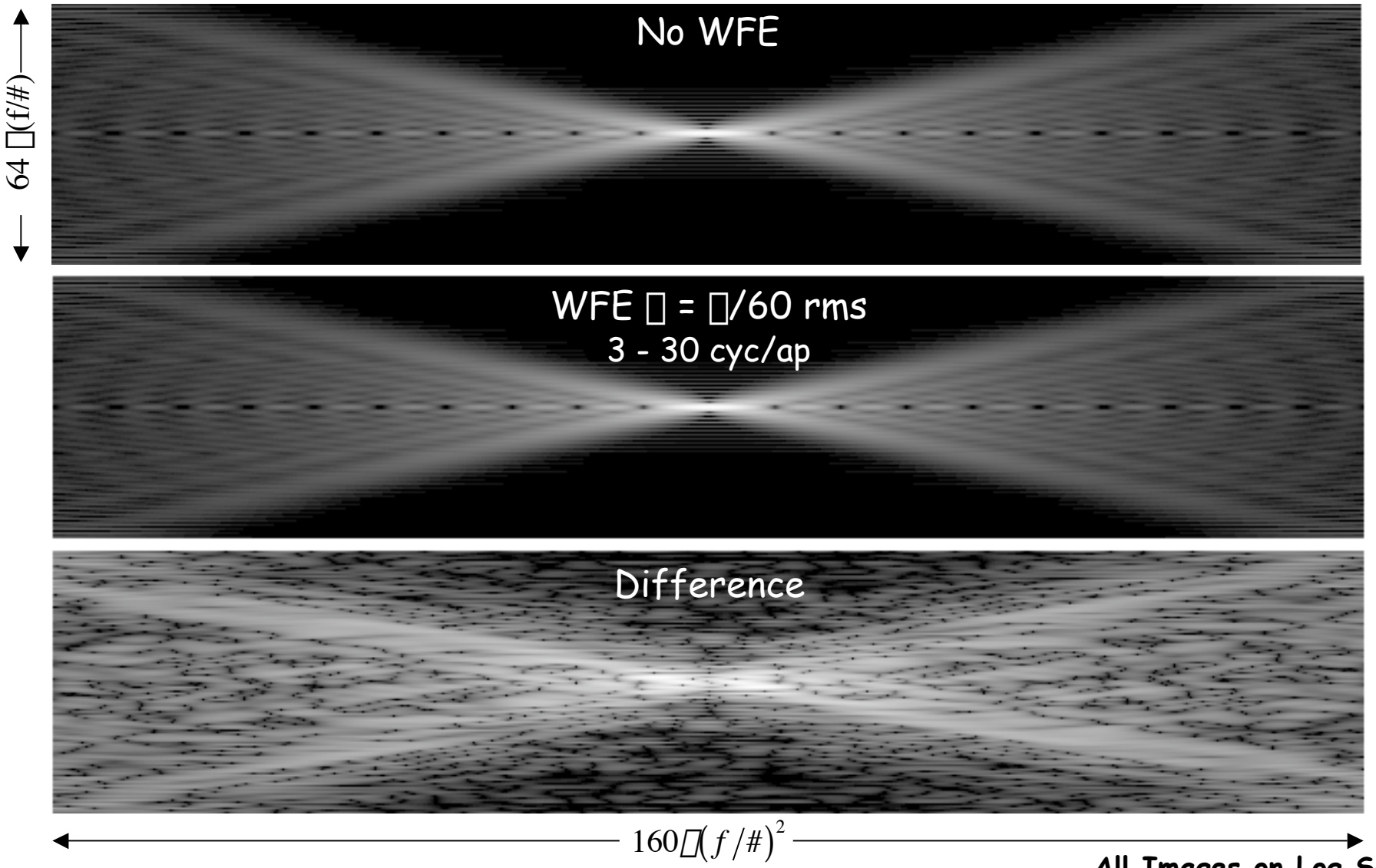
$$PSF(\lambda) \approx PSF_0(\lambda)\left[1 + \frac{\lambda^4}{2}\left(\frac{\Delta x}{D}\right)^4 \lambda^4\right]$$



- Polarization

Through Focus Simulations

R.G. Lyon
02/25/04



All Images on Log Scale

R.G. Lyon
02/25/04

Random Polarization
Classical EM Theory

- Treat each polarization separately in CTF Calculations
- Thermal source @ Infinity => Plane waves @ Telescope
- Vector E-Fields => angular spectrum in plane waves
- Each time step => single polarization state

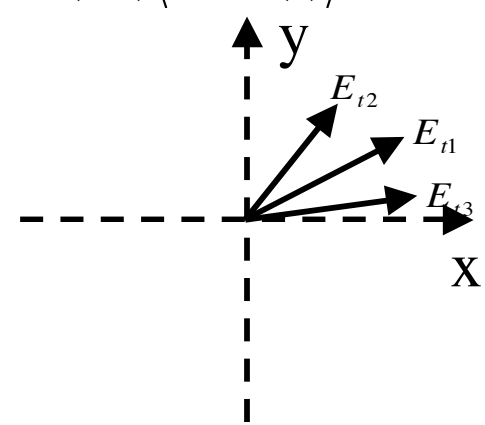
$$\vec{E}(\vec{r},t) = \hat{x}E_x(\vec{r},t)\cos\theta(t) + \hat{y}E_y(\vec{r},t)\sin\theta(t)$$

$$\frac{\partial\theta(t)}{\partial t} << \Delta \qquad P(\theta(t)) = \frac{1}{2\Delta} rect\left[\frac{\theta}{2\Delta}\right]$$

- Intensity:

$$I(\vec{r},t) = \left\langle \vec{E}(\vec{r},t)\cdot\vec{E}(\vec{r},t)\right\rangle = E_x(\vec{r},t)E^*_x(\vec{r},t)\left\langle\cos^2\theta(t)\right\rangle + E_y(\vec{r},t)E^*_y(\vec{r},t)\left\langle\sin^2\theta(t)\right\rangle$$

$$I(\vec{r},t) = \frac{1}{2}E_x(\vec{r},t)E^*_x(\vec{r},t) + \frac{1}{2}E_y(\vec{r},t)E^*_y(\vec{r},t)$$

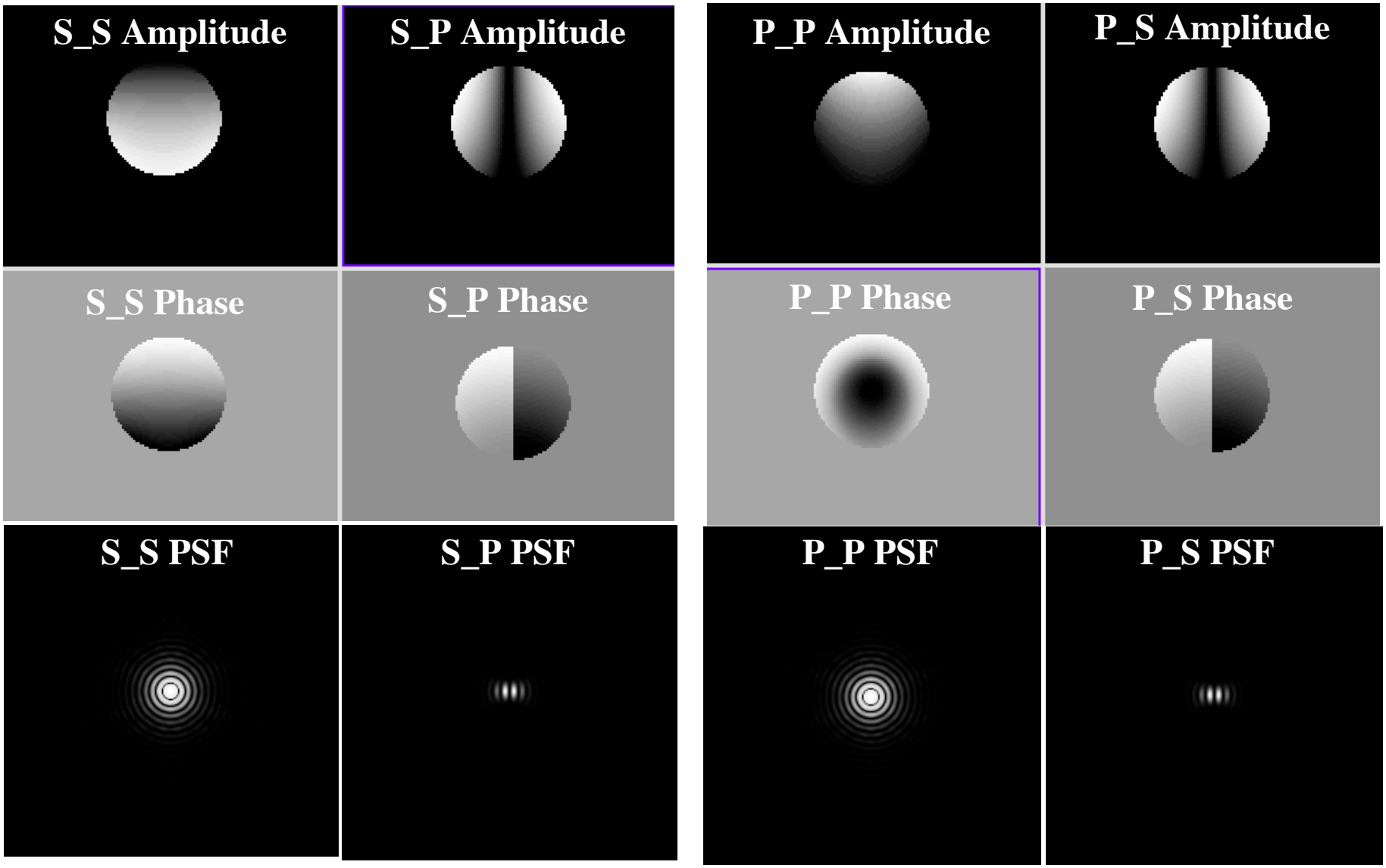


Treat polarizations separately
Average output results

Off-Axis

Gold: n=0.13, k=3.16

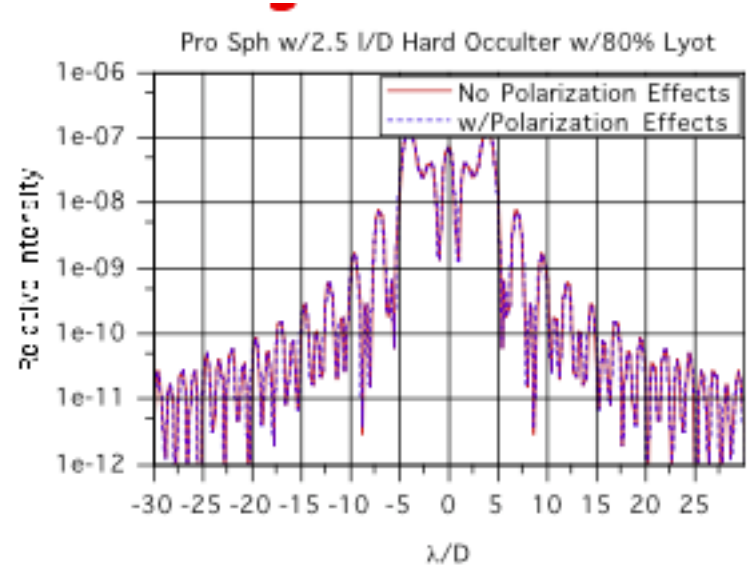
R.G. Lyon
02/25/04



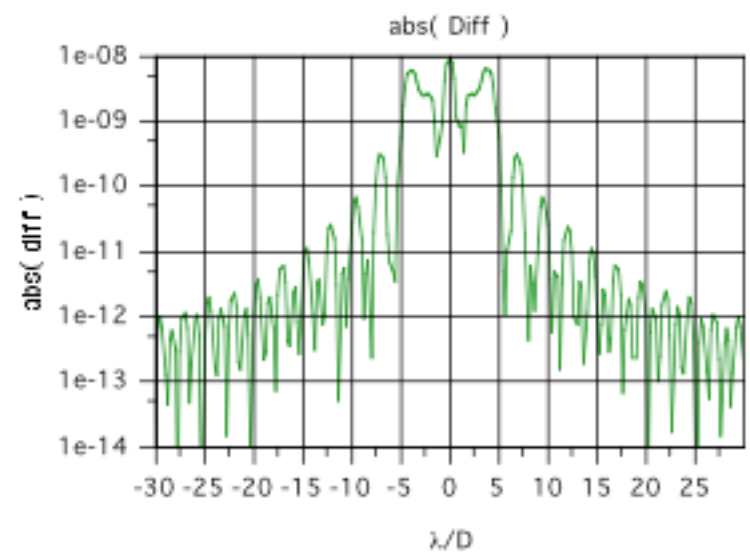
R.G. Lyon
02/25/04

Polarization Leakage

- Polarization Leakage
  ~2 orders of magn < PSF



- Problem for Earths's (TPF)
- Less of a problem for Jupiters



R.G. Lyon
02/25/04

Summary of Techniques

Apodized Square Aperture
- amplitude transmission errors
- mitigates mirror edge effects
- lowers actual wavefront error
- lowers mirror manufact tols
- segmentation of PM for Jupiter detects

Spergel/Kasdin/Vanderbei Apertures
- manufacturing errors (shape & taper)
- advantage => no transms grading i.e. binary
- but how accurate can it be made ?
- Very sensitive to low freq aberrations

Soft-Edge Lyot
- occulter errors, leakage (manuf & misalign)
- Lyot stop errors & align (pupil shear)
- Polychromatic effects

External Occulter (UMBRAS)
- misalign sensitivity ~ cm's
- edge effects, glints and leakage ?
- any method benefits w/ ext occulter
- lower mirror tols due to less starlite
- 2 S/C form flying to ~cm tols

Hypertelescope
- requires coronagraph
- Very high spatial resolution
- Narrow FOV
- Polychromatic effects

Shao Nulling Coronagraph
- WFE < λ/40, IWD ~ 2 λ/D
- Narrow FOV +/- 1 arcsec
- Narrow bandbass (20%)
- No WFS, direct control

Labeyrie Corrector
- Requires speckle phase sensing
- speckle phase correction
- Polychromatic effects