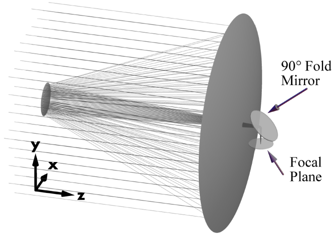
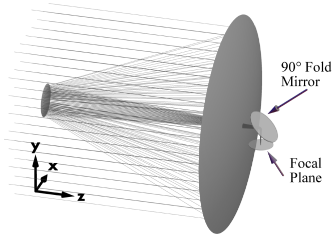


Image quality and polarization: large aperture reflecting telescope systems

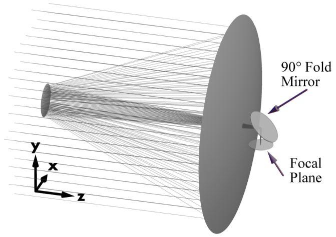
Unpolarized white-light incident

James B. Breckinridge
Caltech
&
College of Optical Sciences



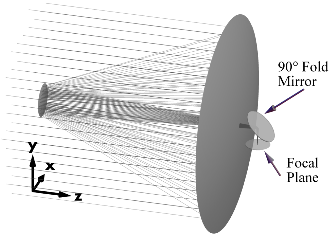
Collaborators

- College of Optical Sciences, University of Arizona
  - Wai Sze Tiffany Lam,
  - Russell Chipman



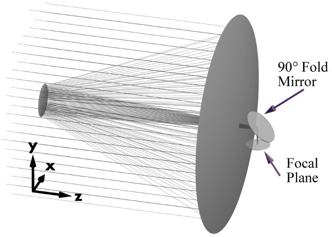
Polarization important in image formation?

- Polarization aberrations dominate some high-performance astronomical telescopes
- Telescope-induced polarization
  - Reduces transmittance
  - Decreases contrast limit
  - Creates a “ghost” PSF to conflict the image
  - Bifurcates the PSF into 2 parts
  - A/O systems cannot correct polarization aberrated wavefronts



Polarization important in image formation?

- In general, to calculate image quality we need
  - First order optics (location, size, orientation & brightness)
  - Geometric (OPD) ray trace [Zernike & Seidel]
  - Diffraction analysis (scalar waves)
  - **Polarization ray trace – Usually ignored**

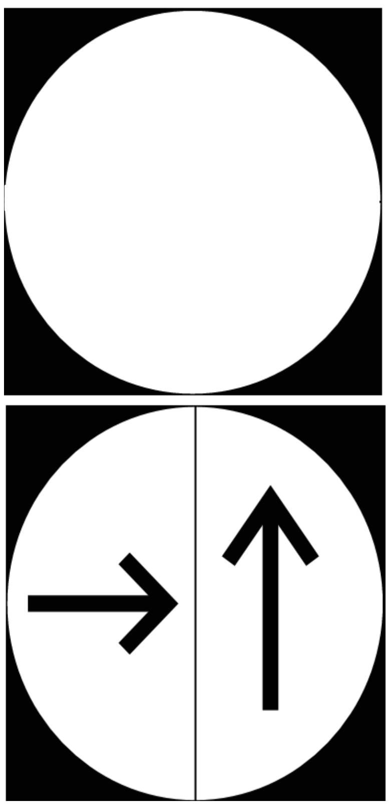


For zero OPD error W=0.0

Proof of polarization role in image formation

Exit pupil

Image plane PSF

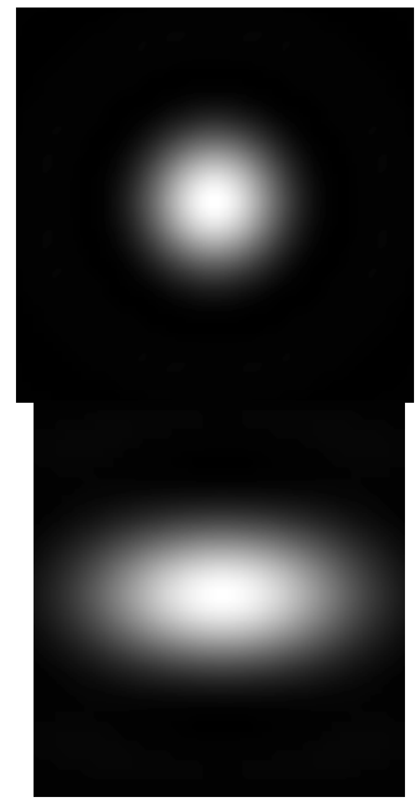


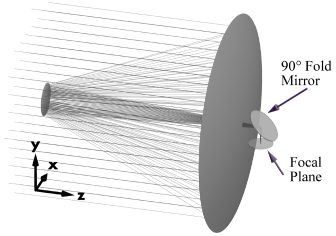
Resolution angle independent

$$|\mathcal{F}|^2$$

Resolution angle dependent

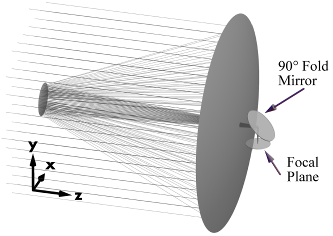
$$|\mathcal{F}|^2$$



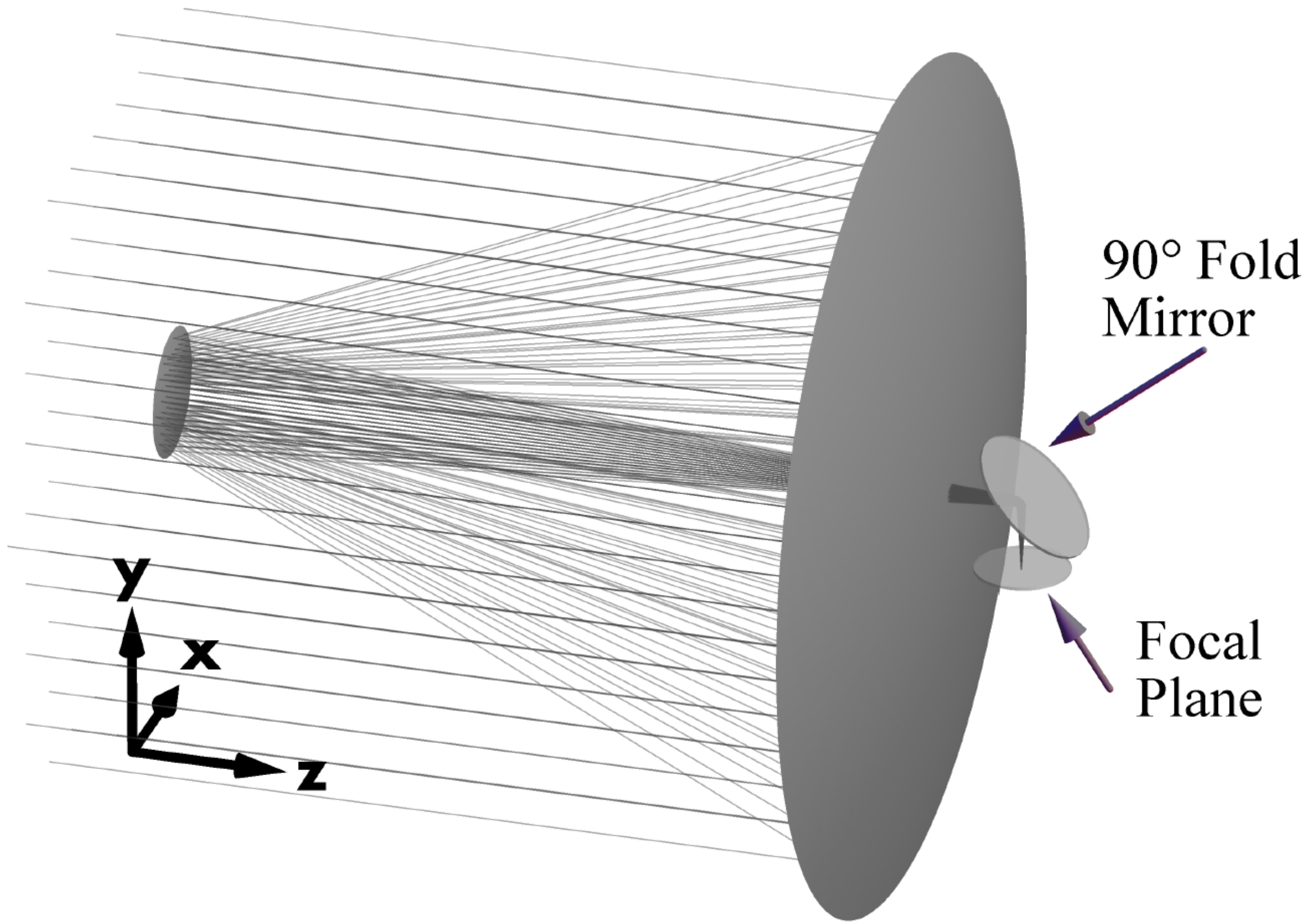


Observation

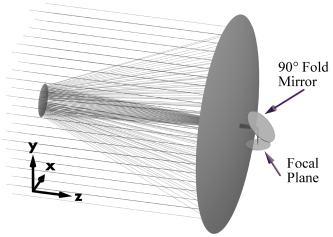
- The shape of the point spread function depends on how polarization changes across the exit pupil



Polarization ray trace a simple 3-element "TYPICAL" optical telescope system

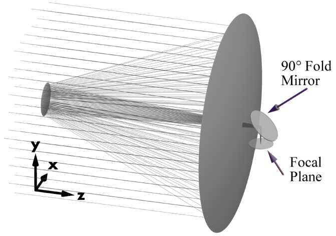


Remember this system layout



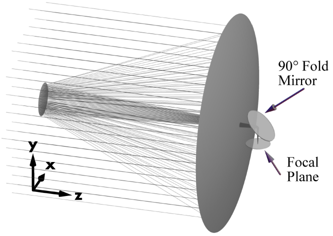
Polarization ray trace a simple 3-element telescope system

- Primary, secondary.
- Tertiary fold mirror deviates the converging beam by 90 degrees onto the focal plane
- 2.4 meter primary has an F/#=1.2
- Power on the secondary is such that the Cassegrain F/#=8.
- Geometrical optics used to adjust curvatures on primary and secondary to give ***zero geometric aberrations on axis***



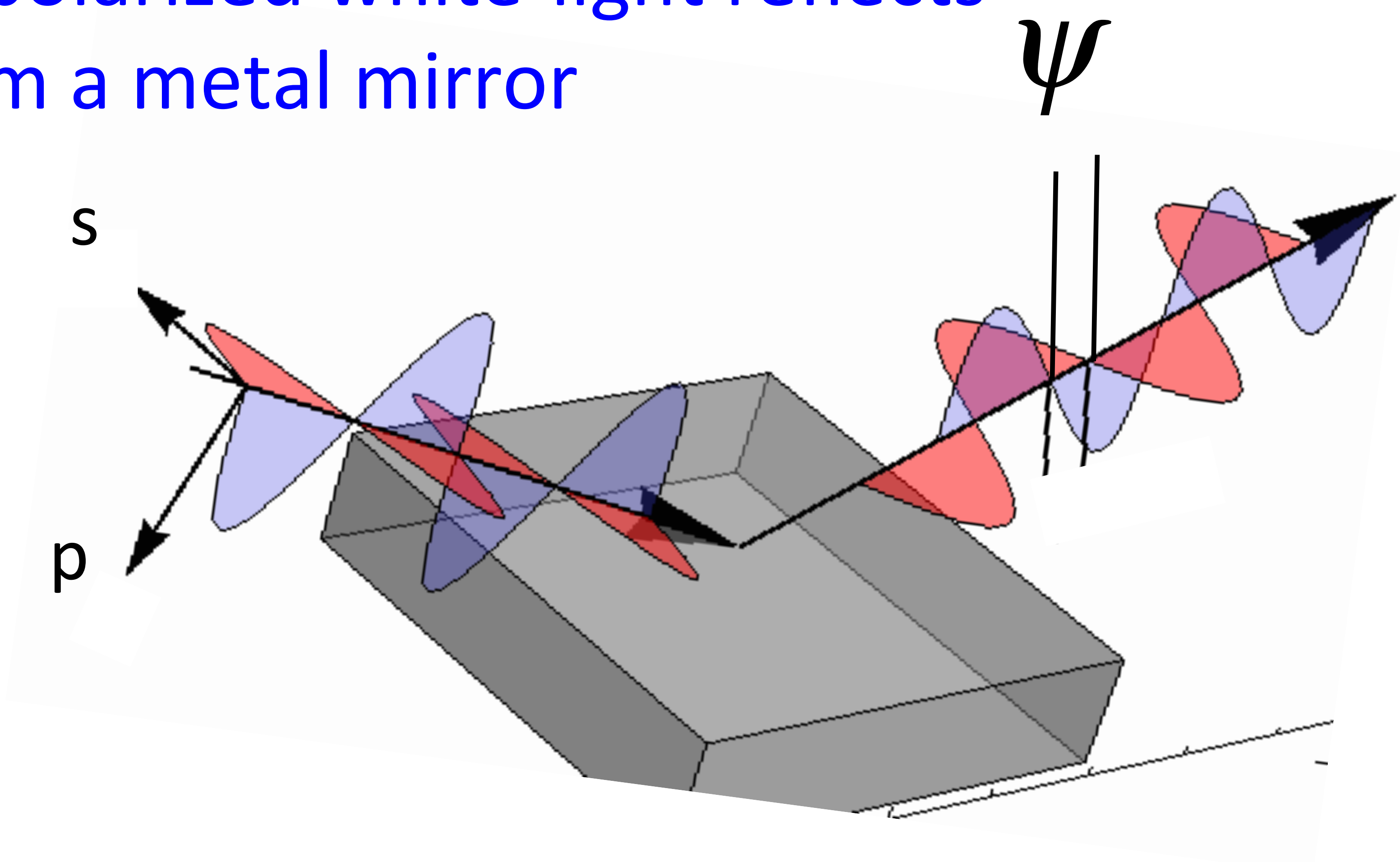
Decompose white-light into polarization components:

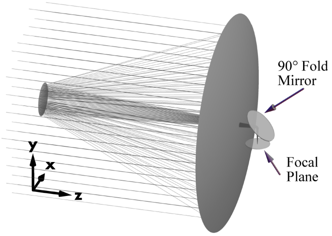
- We can select any orthonormal basis set for the ray trace
- Select the easiest for for intuition
- Use that component perpendicular to the plane of reflection (⊥) **&**
- That component parallel to the plane of reflection (||)



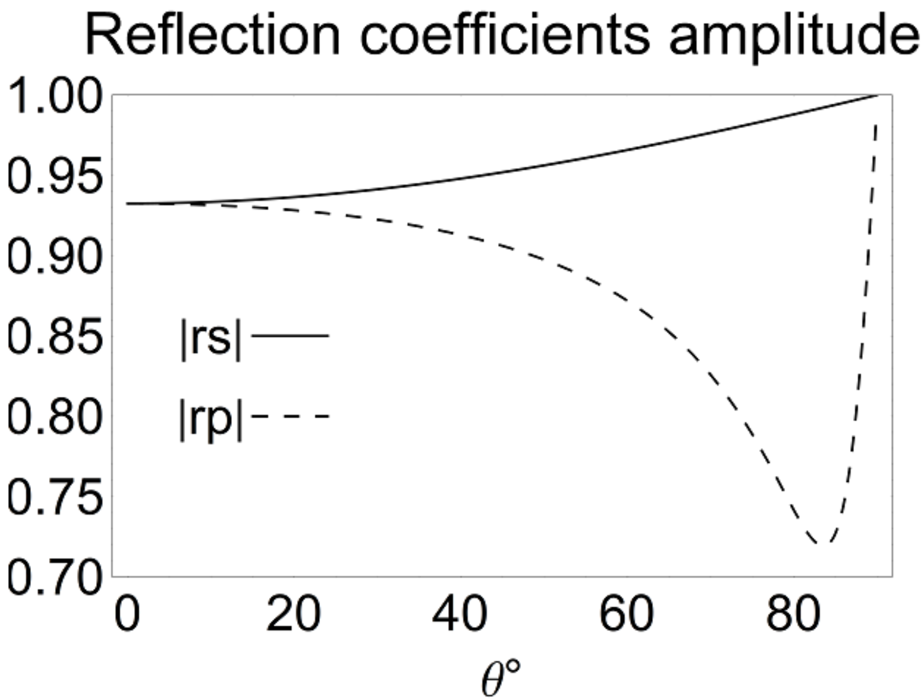
Orthogonal linear polarization

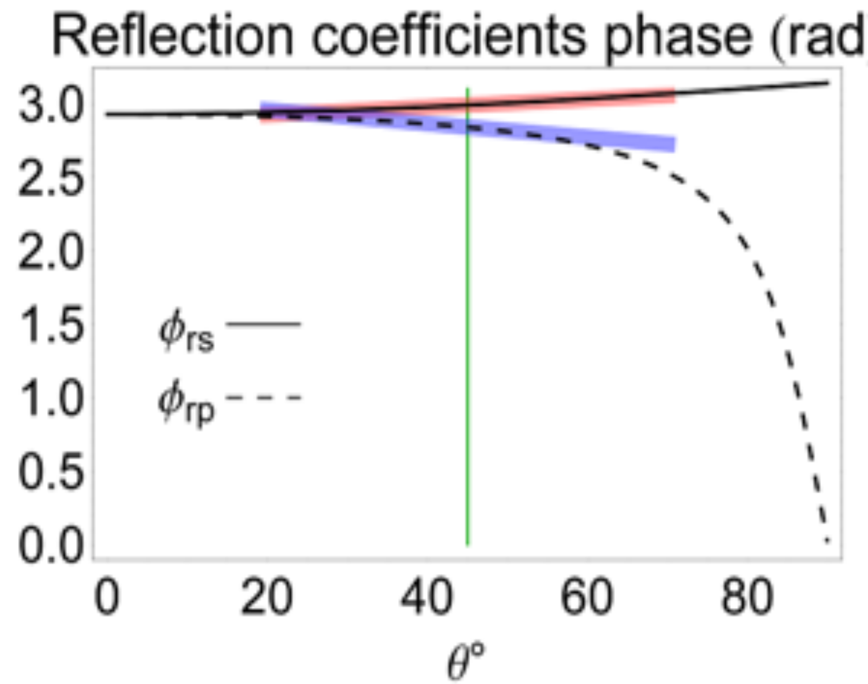
Unpolarized white-light reflects from a metal mirror

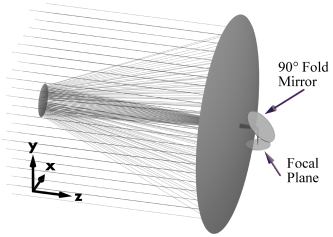




Reflection coefficients for Al @ 800 nm

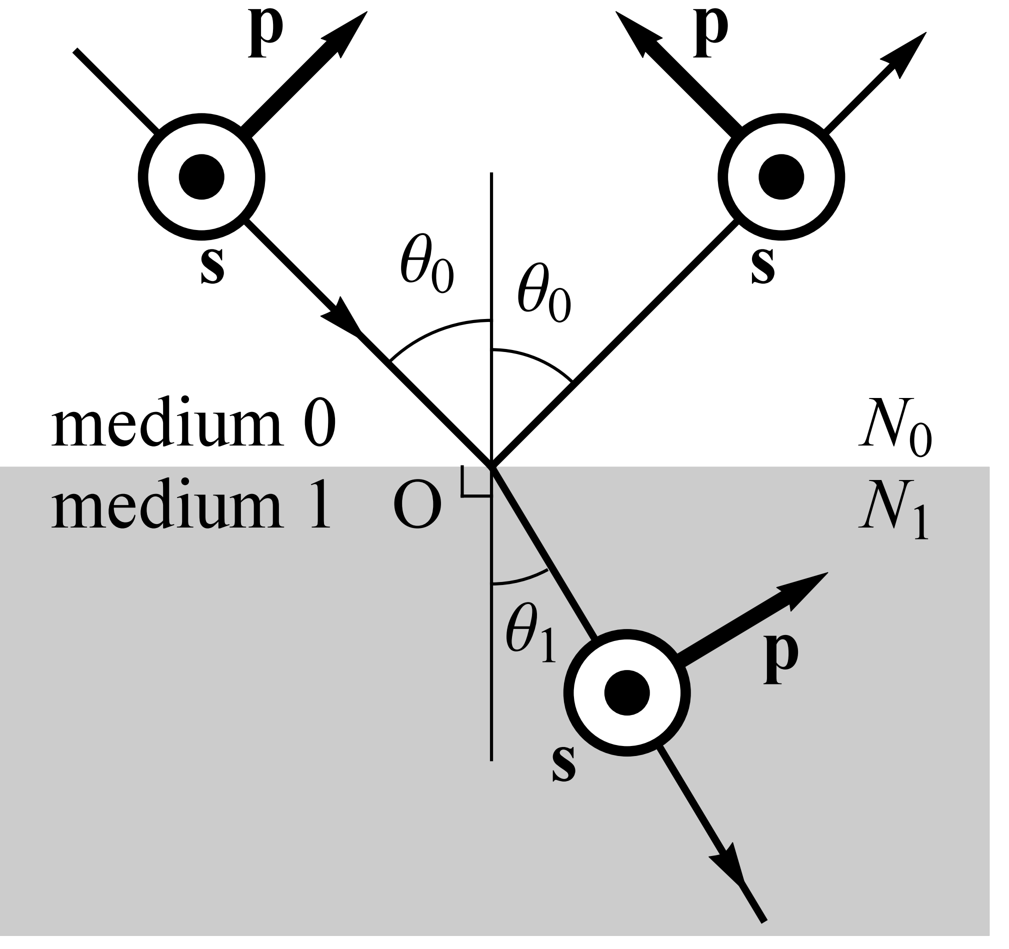


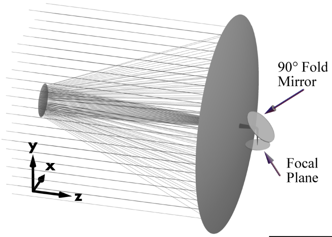




Physical optics source of the polarization

- Astronomical telescopes use reflections from tilted surfaces
- A beam incident onto a dielectric or a metal surface becomes partially polarized
- Metals change optical phase

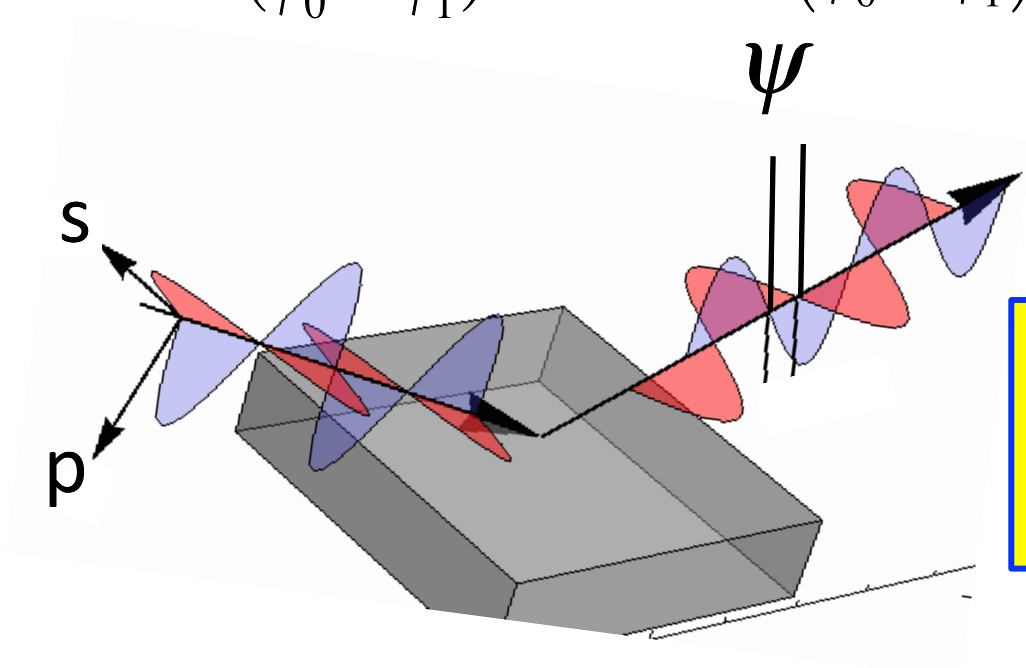




Fresnel equations & definitions

$$N = n - ik \qquad \phi_1 = \arccos\left\{\frac{\sqrt{N_1^2 - N_0^2 \sin^2 \phi_0}}{N_1}\right\}$$

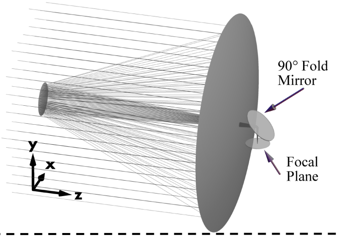
$$r_p = \frac{\tan(\phi_0 - \phi_1)}{\tan(\phi_0 + \phi_1)} \qquad r_s = \frac{-\sin(\phi_0 - \phi_1)}{\sin(\phi_0 + \phi_1)} \qquad \tan\psi = |r_p| / |r_s|$$

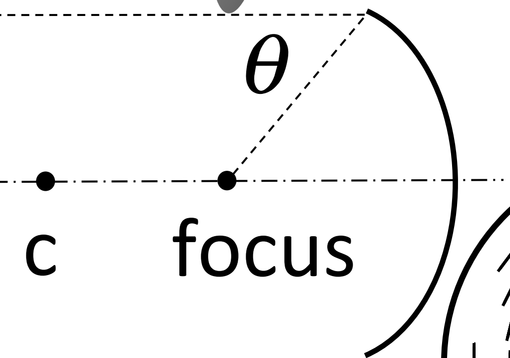


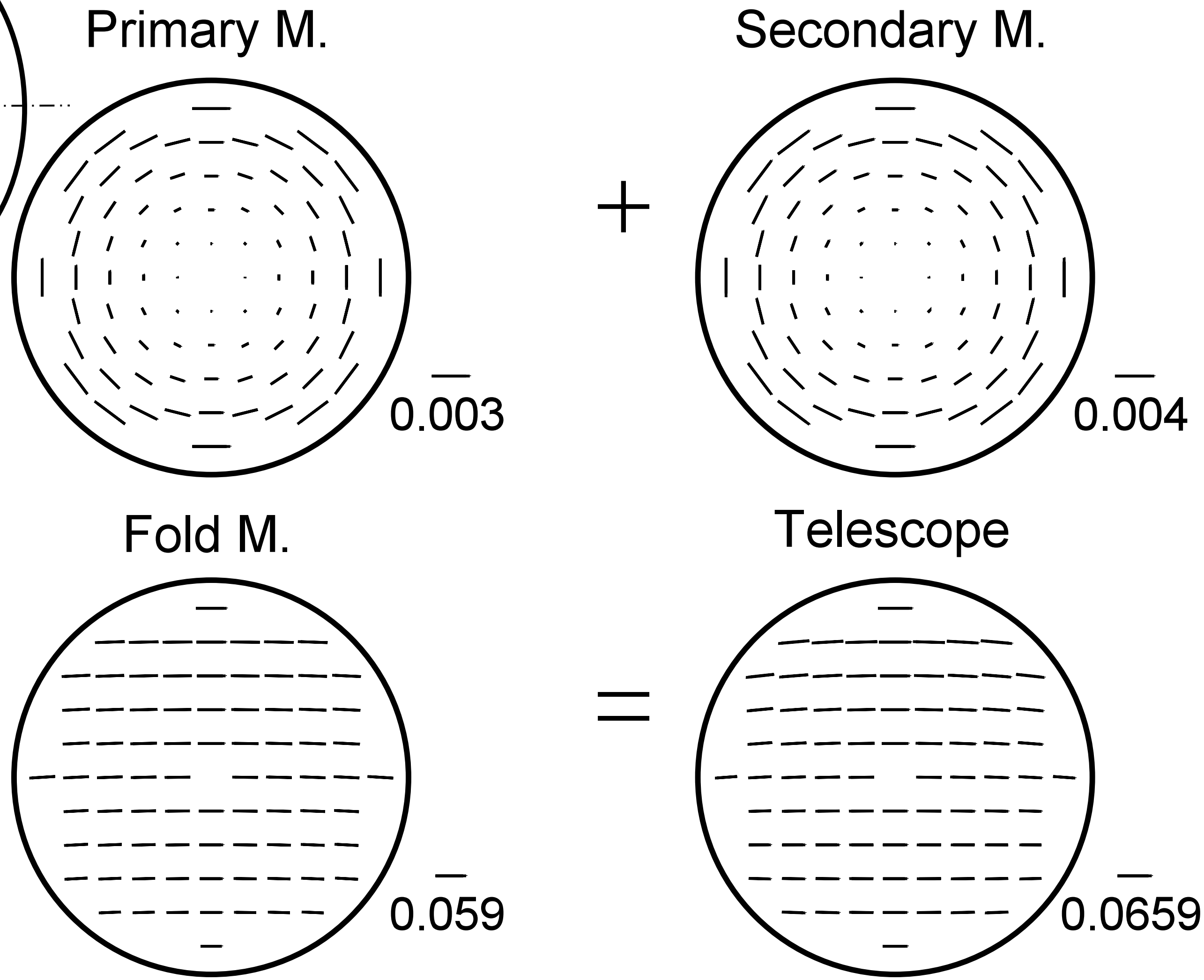
ψ is called retardance

$$\frac{r_s - r_p}{r_s + r_p} = \text{diattenuation}$$

$$\frac{r_s - r_p}{r_s + r_p} = \text{diattenuation maps}$$

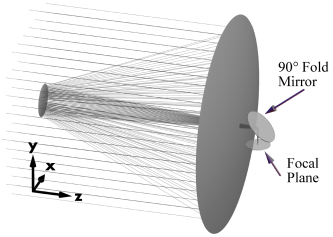


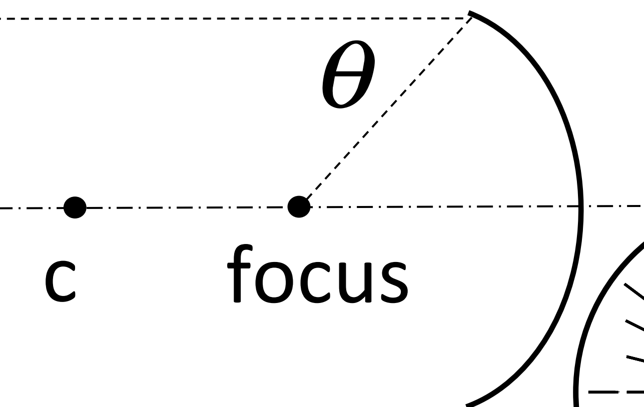


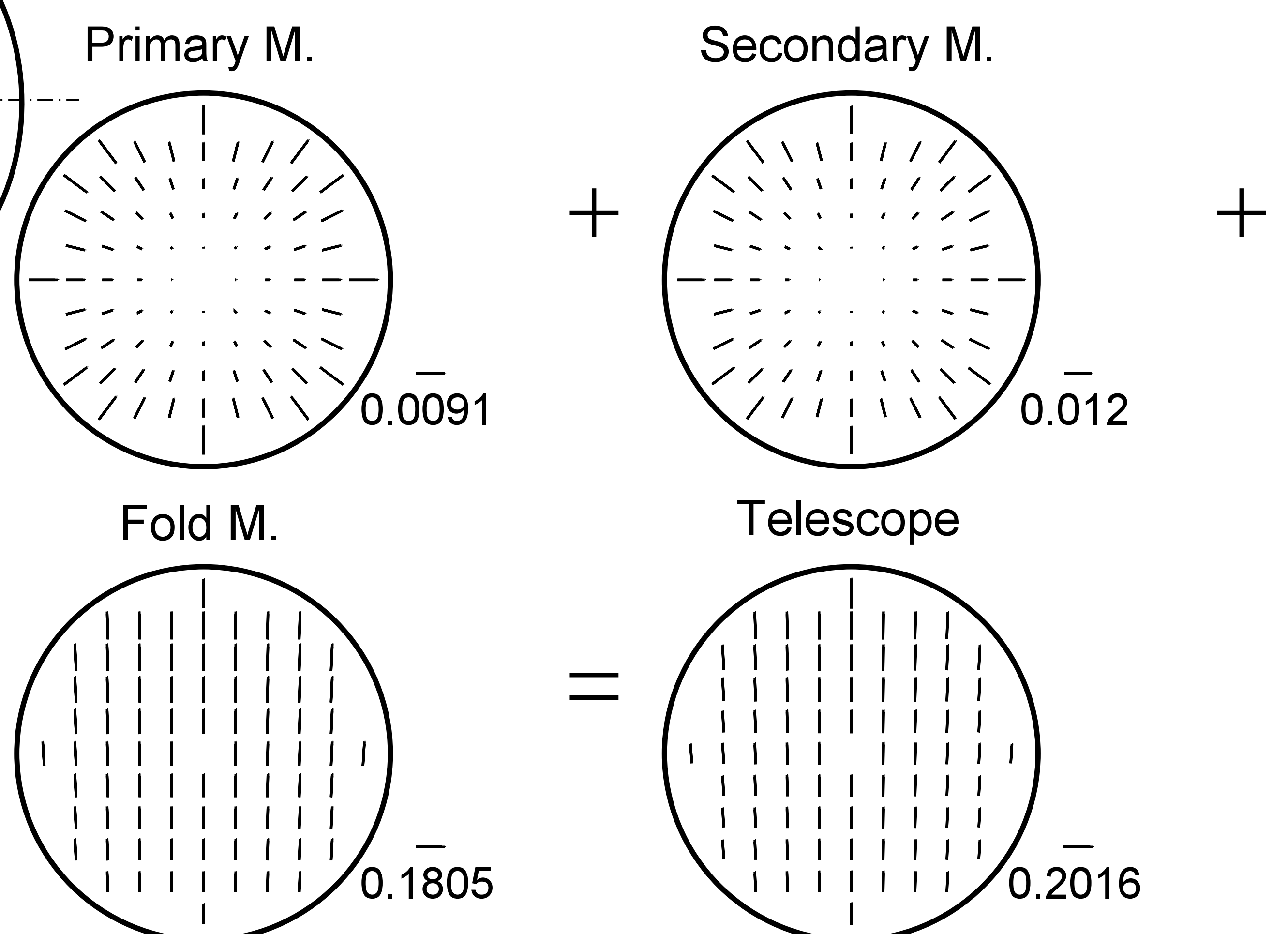


Retardance maps

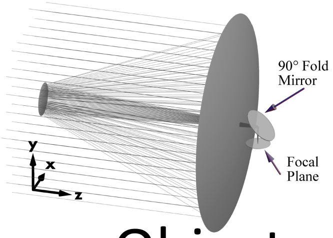
$$\tan\psi = \left|r_p\right| / \left|r_s\right|$$

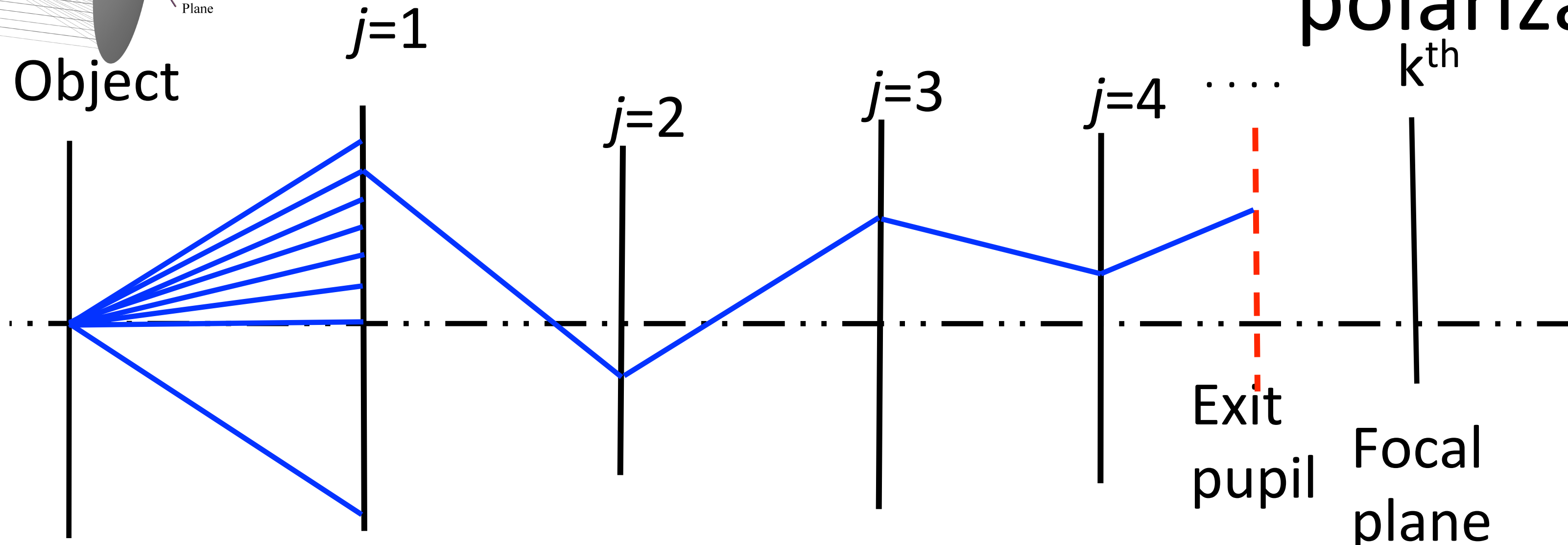






How to calculate the PSF for each polarization

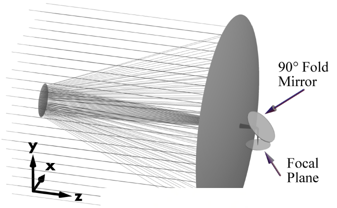




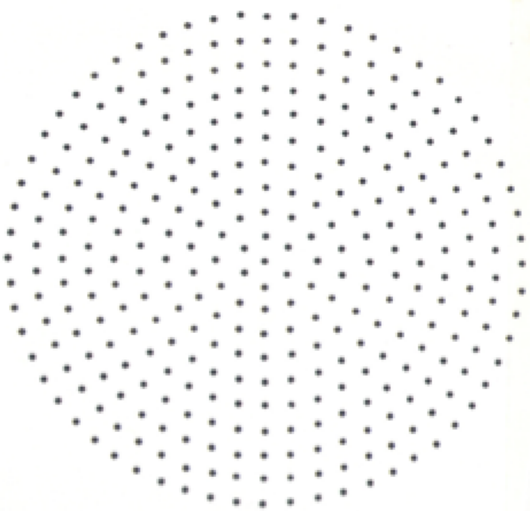
Based on the direction cosine at each surface and the physical properties of each surface $(n-ik)$ we use the Fresnel equations to calculate the amplitude attenuation and the phase change for each ray at each surface

Trace only to the exit pupil that is, accumulate the phase and amplitude points to the exit pupil

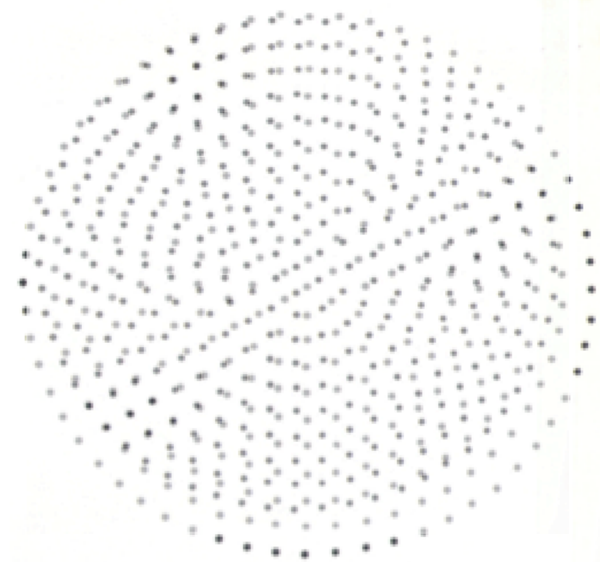
For $\perp$ and then $\|$ light



Entrance to exit pupil mapping



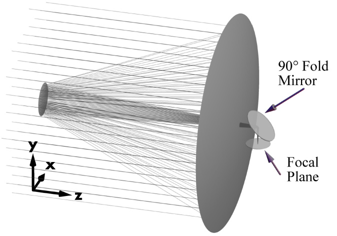
Entrance pupil



Jones Exit pupil

Because of the metal coated mirrors there are 2 sets of exit pupil points, one for each orthogonal Polarization.

Index of refraction depends on polarization state of the ray. A single point in the entrance pupil is mapped to two points in the exit pupil



How do we analyze this?

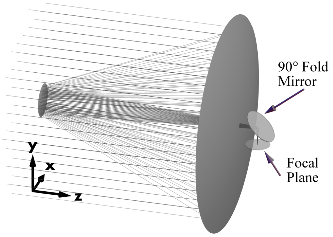
$$\mathcal{R}_{\vec{Y}=>\vec{X}}$$

Is the complex reflection coefficient **calculated using the Fresnel equations** for the cross-coupling of *Y* polarized light into *X*

$$J_{XY} = A_{\vec{X}}(x,y) = A_{\vec{Y}}(x,y) \cdot \mathcal{R}_{\vec{Y}=>\vec{X}}$$

Group equations like this

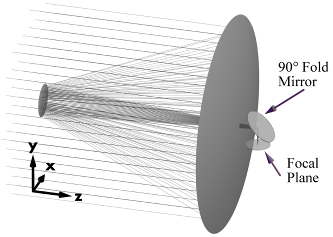
$$\begin{cases} J_{XX} = A_{XX} e^{i\phi_{XX}} \ ; \ J_{YX} = A_{YX} e^{i\phi_{YX}} \\ J_{XY} = A_{XY} e^{i\phi_{XY}} \ ; \ J_{YY} = A_{YY} e^{i\phi_{YY}} \end{cases}$$



How do we analyze this?

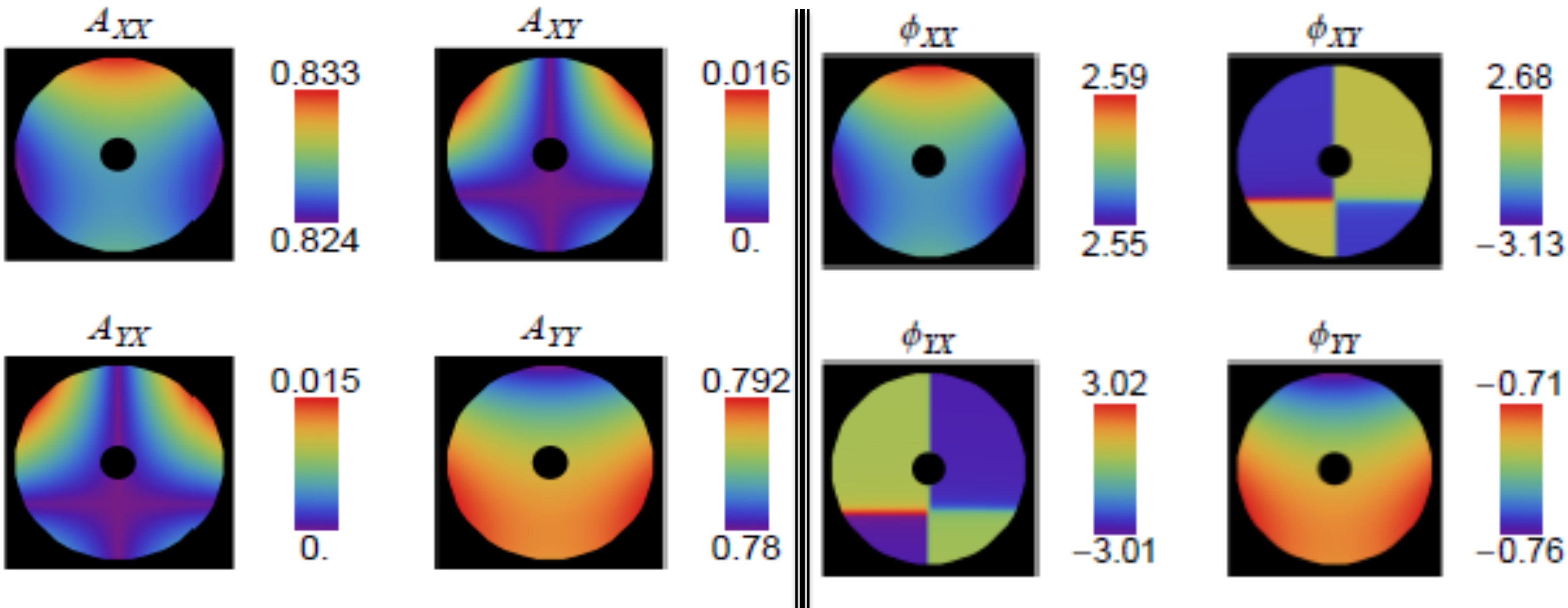
- Write the Jones pupil as a 2 x 2 matrix that contains complex terms

$$\mathbf{J} = \begin{pmatrix} J_{XX} & J_{YX} \\ J_{XY} & J_{YY} \end{pmatrix} \equiv \begin{pmatrix} A_{XX}\, e^{i\phi_{XX}} & A_{YX}\, e^{i\phi_{YX}} \\ A_{XY}\, e^{i\phi_{XY}} & A_{YY}\, e^{i\phi_{YY}} \end{pmatrix}$$

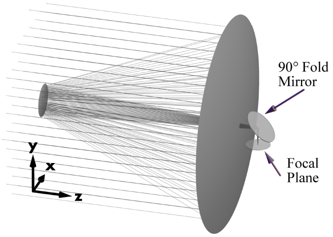


Maps of Jones Pupil

Radians



$$\mathbf{J} = \begin{pmatrix} J_{XX} & J_{YX} \\ J_{XY} & J_{YY} \end{pmatrix} \equiv \begin{pmatrix} A_{XX}\, e^{i\phi_{XX}} & A_{YX}\, e^{i\phi_{YX}} \\ A_{XY}\, e^{i\phi_{XY}} & A_{YY}\, e^{i\phi_{YY}} \end{pmatrix}$$

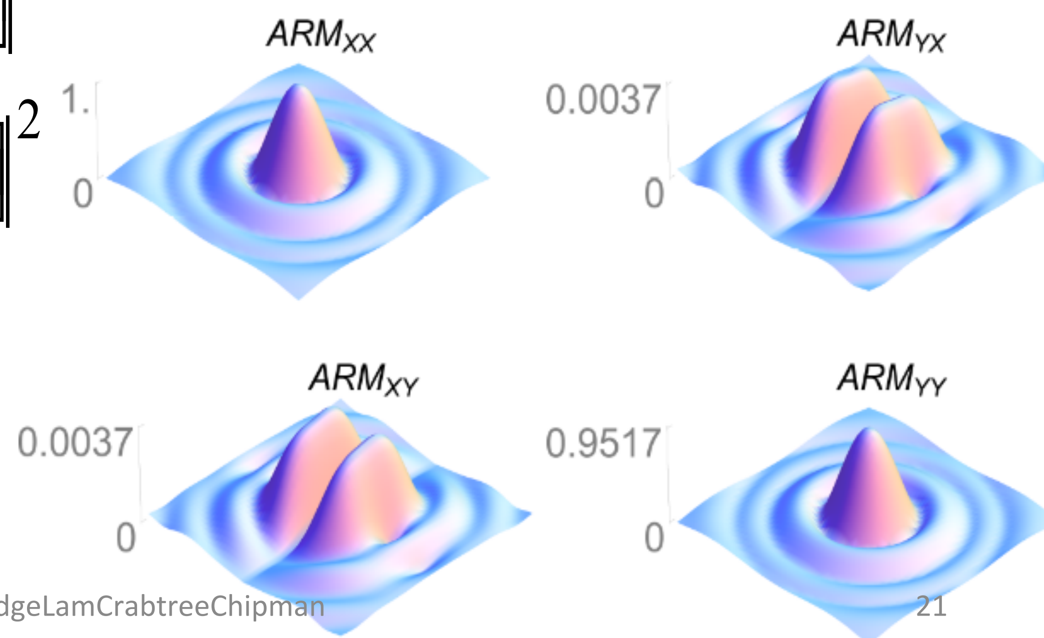


Use the FT relation between pupil & image & propagate this to the image plane

Amplitude Response Matrix $= \mathbf{ARM} = \begin{pmatrix} \Im\left[J_{XX}(x,y)\right] & \Im\left[J_{YX}(x,y)\right] \\ \Im\left[J_{XY}(x,y)\right] & \Im\left[J_{YY}(x,y)\right] \end{pmatrix}$

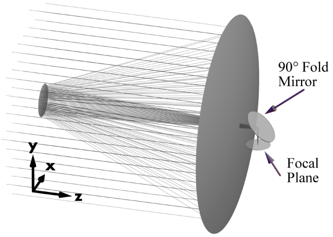
$$\left|\Im\left[J_{XX}(x,y)\right]\right|^2 \quad \left|\Im\left[J_{YX}(x,y)\right]\right|^2$$

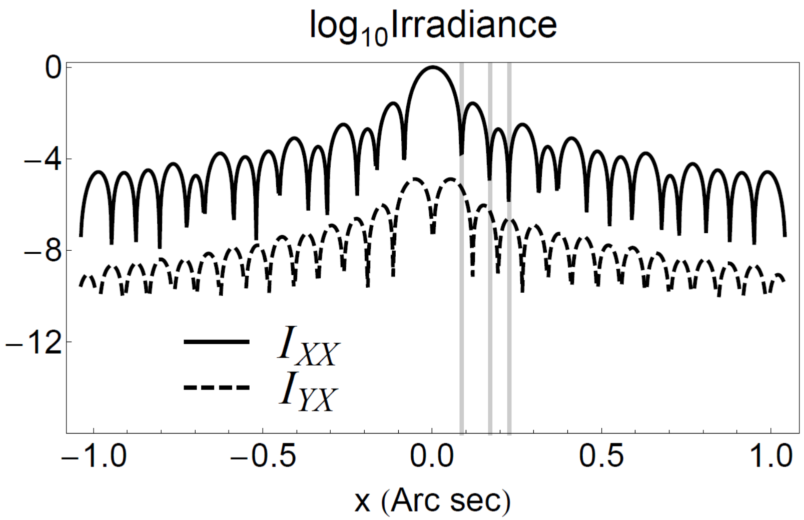
$$\left|\Im\left[J_{XY}(x,y)\right]\right|^2 \quad \left|\Im\left[J_{YY}(x,y)\right]\right|^2$$

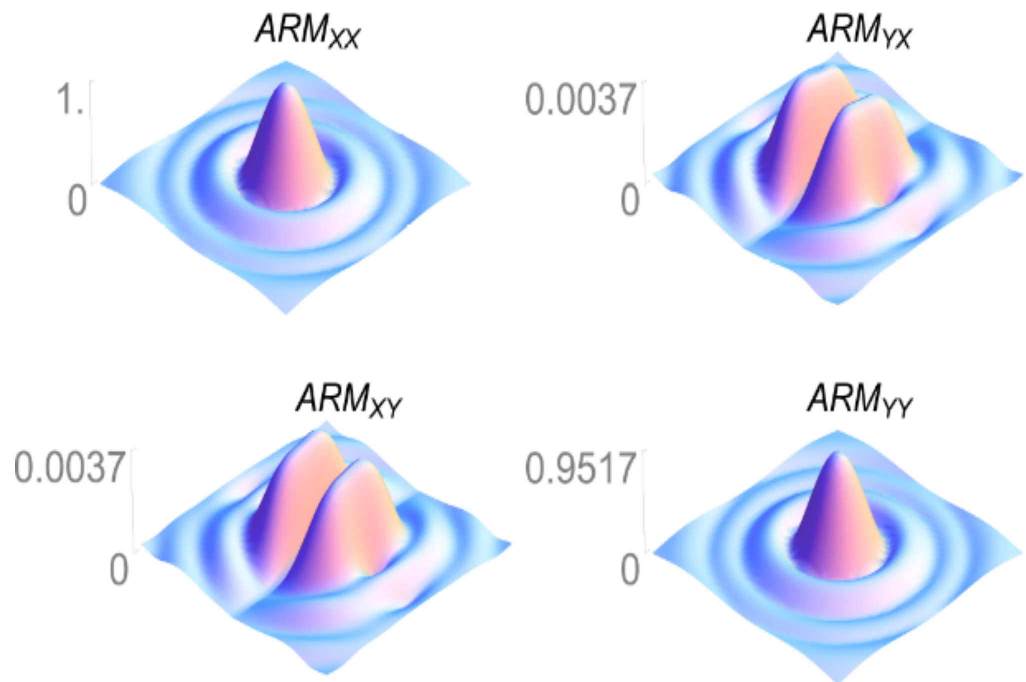


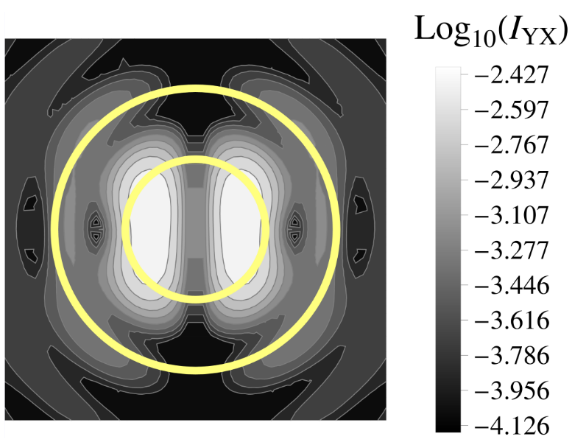
Intensities

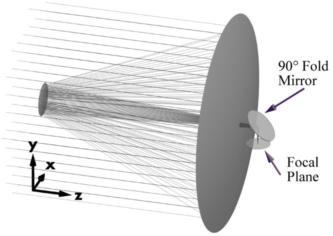
Polarization cross talk & the "ghost" PSF







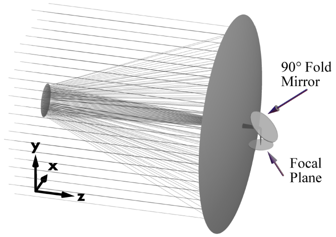




Performance of the "typical" 2.4 meter F#=8 telescope with one fold

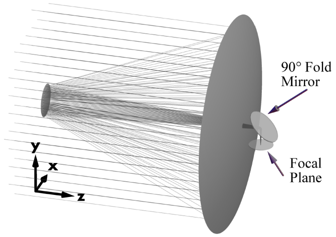
Table 1 The system PSF's flux, the radius of encircle energy, the PSF shears and the PSF ellipticity for *X* and *Y* polarized incident light are shown.

Flux in PSF	$\frac{\text{flux of } I_{YX}}{\text{flux of } I_{XX}} = 0.0048\%$	$\frac{\text{flux of } I_{YY}}{\text{flux of } I_{XX}} = 90.6\%$	$\frac{\text{flux of } I_{YX}}{\text{flux of } I_{XX}} = 0.0046\%$
	$\frac{\text{Peak of } I_{Y}}{\text{Peak of } I_{X}} = 90.6\%$		$\frac{\text{Peak of } (I_X - I_Y)}{\text{Peak of } I_{X}} = 9.6\%$
Radius of 90% encircled energy in object space	$r_{XX} = r_{YY} = 0.15$ arc sec		$r_{YX} = r_{XY} = 0.36$ arc sec
PSF shear in object space	Between I_X and I_Y : 0.625 mas		Between I_X and I_X-I_Y : 5.820 mas
Ellipticity of PSF	Unpolarized incident light 7.502×10^{-6}	*X*-polarized incident light 0.00199	*Y*-polarized incident light 0.00208



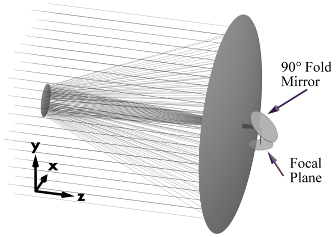
Findings from this study for a“typical” telescope imaging system

- Each mirror is a partial polarizer
- PSF bifurcates into two parts
- Wavefront aberrations are polarization dependent and differ by several nm
- Aberrations cannot be corrected using a polarizer in the path
- The PSF has a distorted ghost whose intensity depends on the number of reflecting surfaces
- Magnitude of the aberrations depends on specific design and packaging

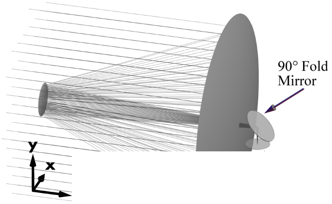


Summary

- There is a 32 milli-waves difference in the wavefront aberrations (tilt, coma, astigmatism, spherical, etc.) between $\parallel$ and $\perp$
- Shift between the PSF's for *X* and *Y* polarizations by about 0.625 masec
- The *X* and *Y* polarizations also show a 10% difference in intensity transmittance => unpolarized sources to exit partially polarized into the instrument packages.
- The telescope coatings cause polarization variations throughout the PSF, particularly into the diffraction rings, which may complicate polarization measurements of exoplanets and debris rings in coronagraphs.
- Adaptive optics systems cannot simultaneously correct the wavefront aberrations of both polarizations.
- The light from one polarization which is coupled into its orthogonal state is not coherent with respect to the orthogonal state, and forms a separate faint and much larger PSF superposed on the Airy diffraction pattern.



Thank you



Mitigation Phase plate

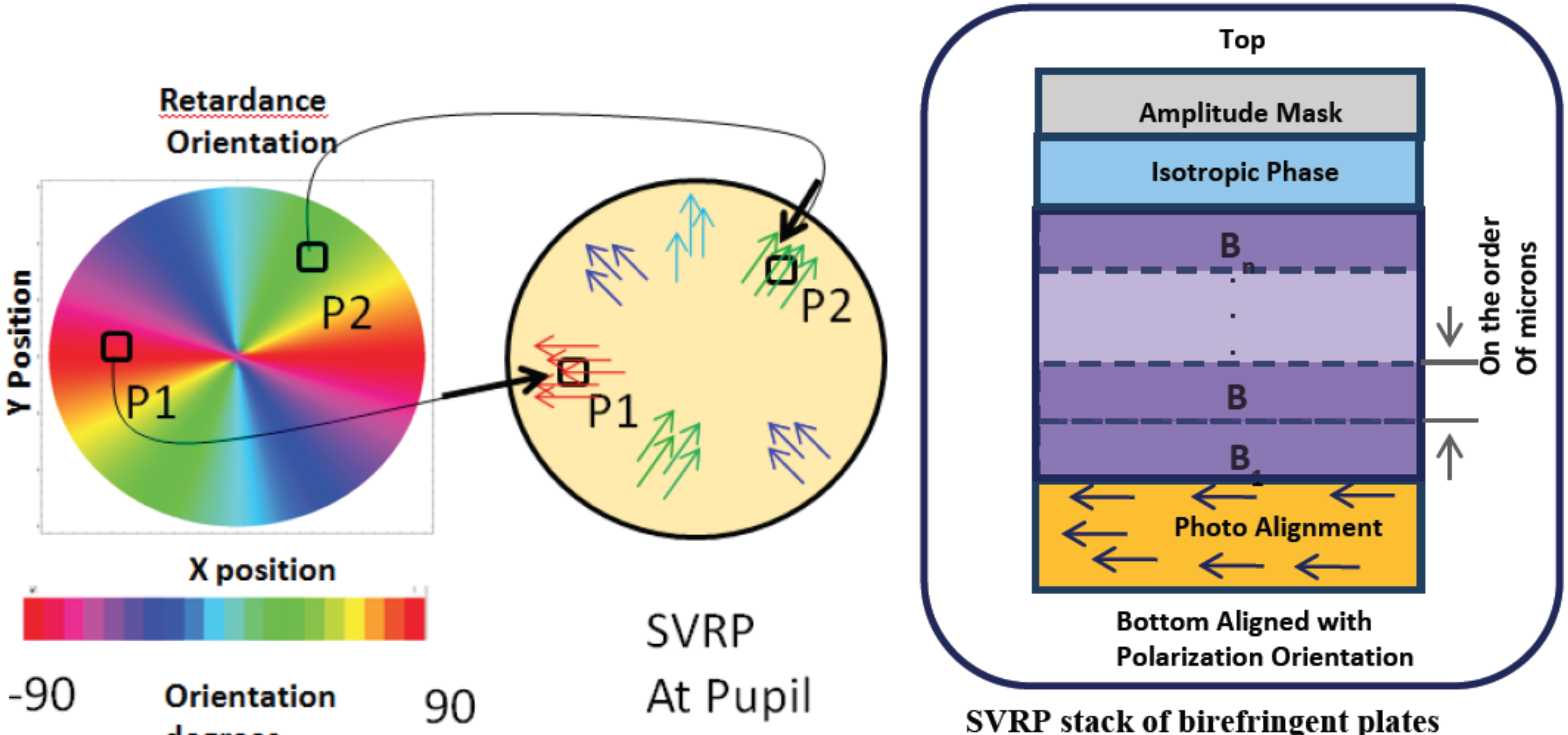
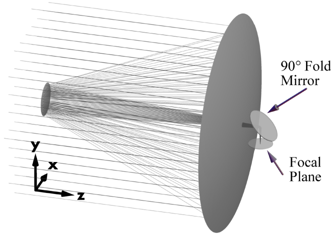
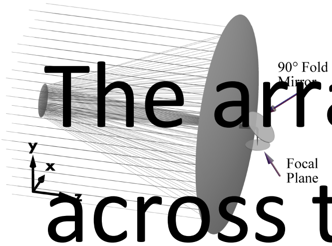


Figure 4. Photo alignment layer of a SVRP plate. (a) shows a spatially variable retarder plate (SVRP) face on (x,y) with retardance direction indicated by the colors shown in the stripe below which maps color into orientation in degrees as shown. (b) shows two particular regions, P1 and P2 which have two different polarization states and orientation are shown. (c) shows a diagram of the typical stack or sandwich. The bottom layer is a layer of homogeneous dielectric oriented to the polarization direction. Birefringent layers of B_1, B_2...B_n will be deposited with thickness layers and specific process recipe calculated and optimized to compensate for the Fresnel polarization of light reflected form the telescope.



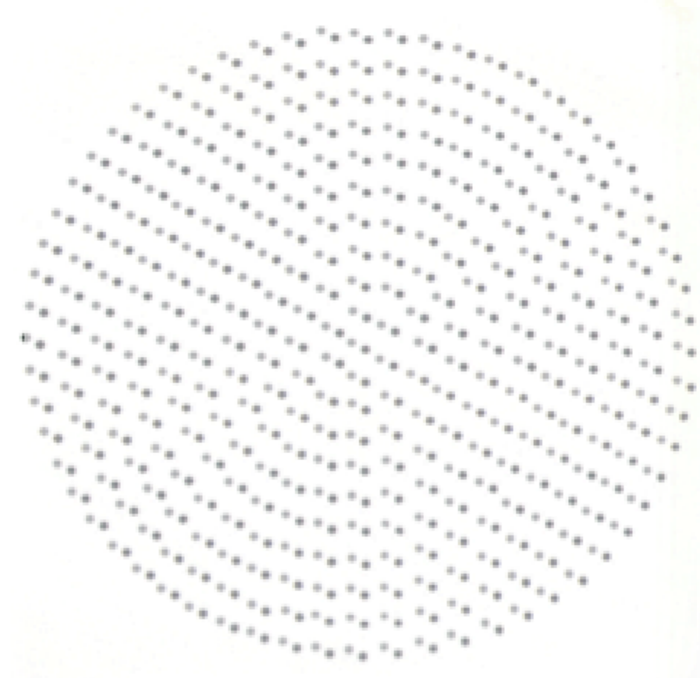
Summary

- Several methods of mitigating polarization aberration can possibly reduce polarization aberrations, including configuring elements to balance polarization aberrations, such as the opposite contributions to diattenuation from lenses and mirrors, or the aberration reduction from “crossed mirrors”, and including polarization aberration compensators such as spatially variable retardance and diattenuation plates.
- Even if you are observing an unpolarized source, internal instrument induced polarization alters the telescope performance



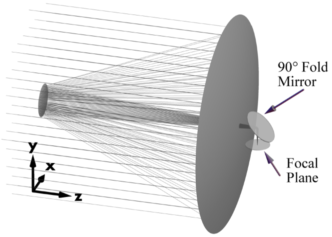
The array of numbers across the exit pupil is called the Jones Pupil,

$$\mathbf{J}$$

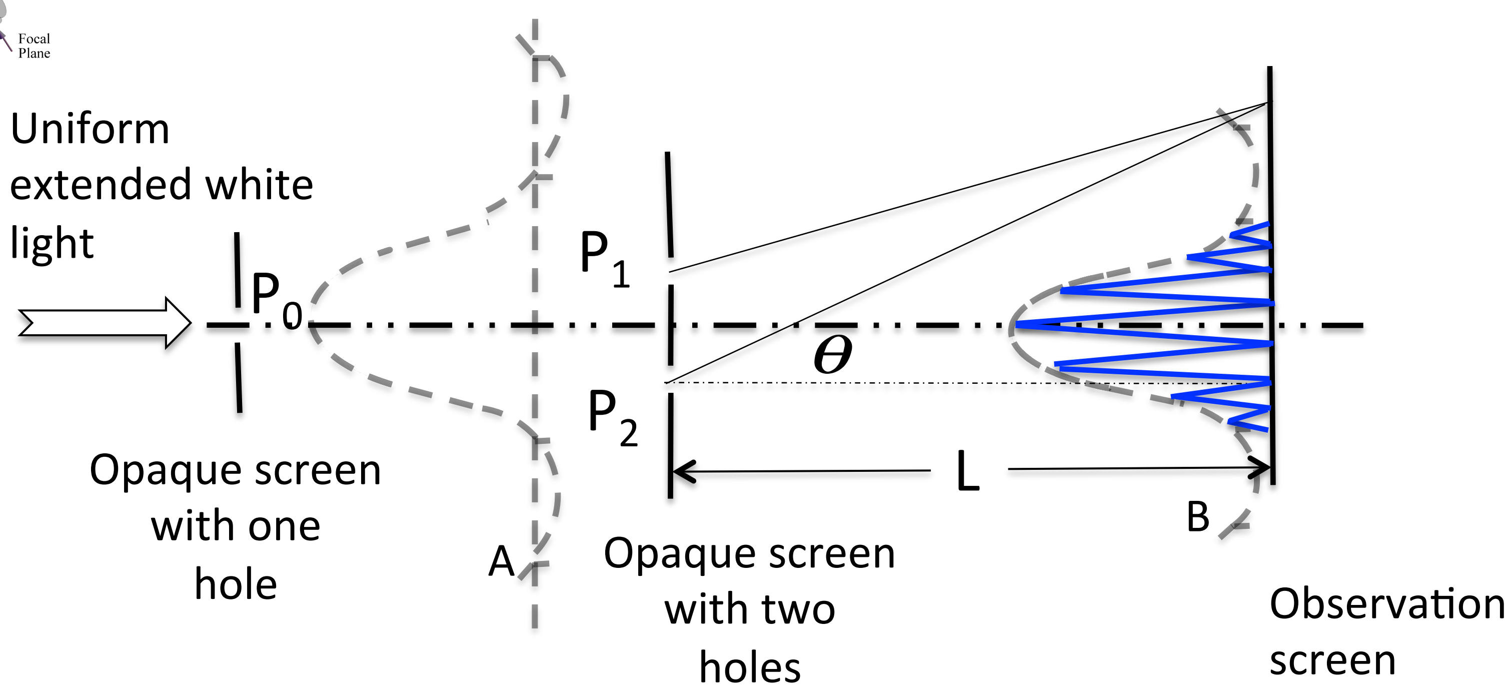


It is a 2 x 2 matrix of complex numbers, shown below

$$\mathbf{J} = \begin{pmatrix} J_{XX} & J_{YX} \\ J_{XY} & J_{YY} \end{pmatrix} \equiv \begin{pmatrix} A_{XX}\, e^{i\phi_{XX}} & A_{YX}\, e^{i\phi_{YX}} \\ A_{XY}\, e^{i\phi_{XY}} & A_{YY}\, e^{i\phi_{YY}} \end{pmatrix}$$

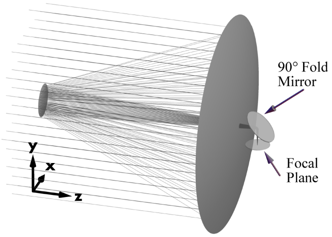


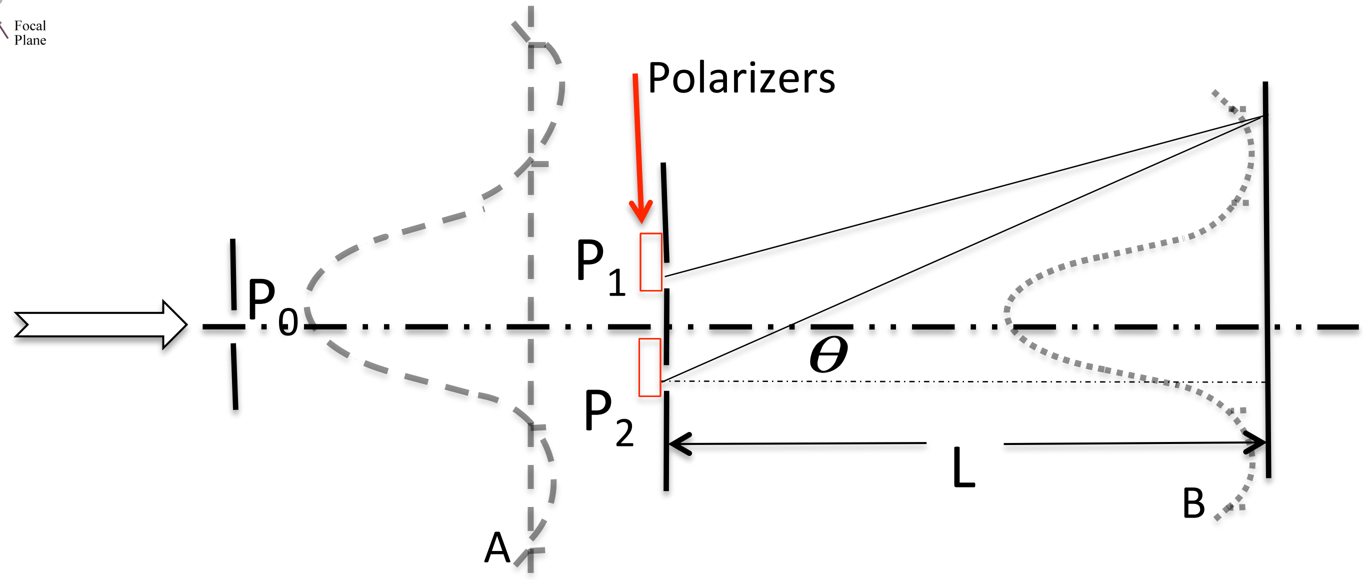
Double slit experiment



- Curve B is the diffraction pattern from holes P1 and P2
  - Spacing of the fringes underneath curve B is related to the separation of the holes P_1 and P_2
  - Visibility (contrast) of these fringes underneath curve B is given by the degree of correlation (coherence) of the fluctuating electromagnetic fields between P_1 and P_2.

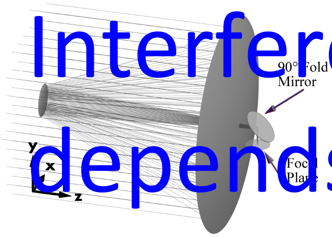
Double slit experiment

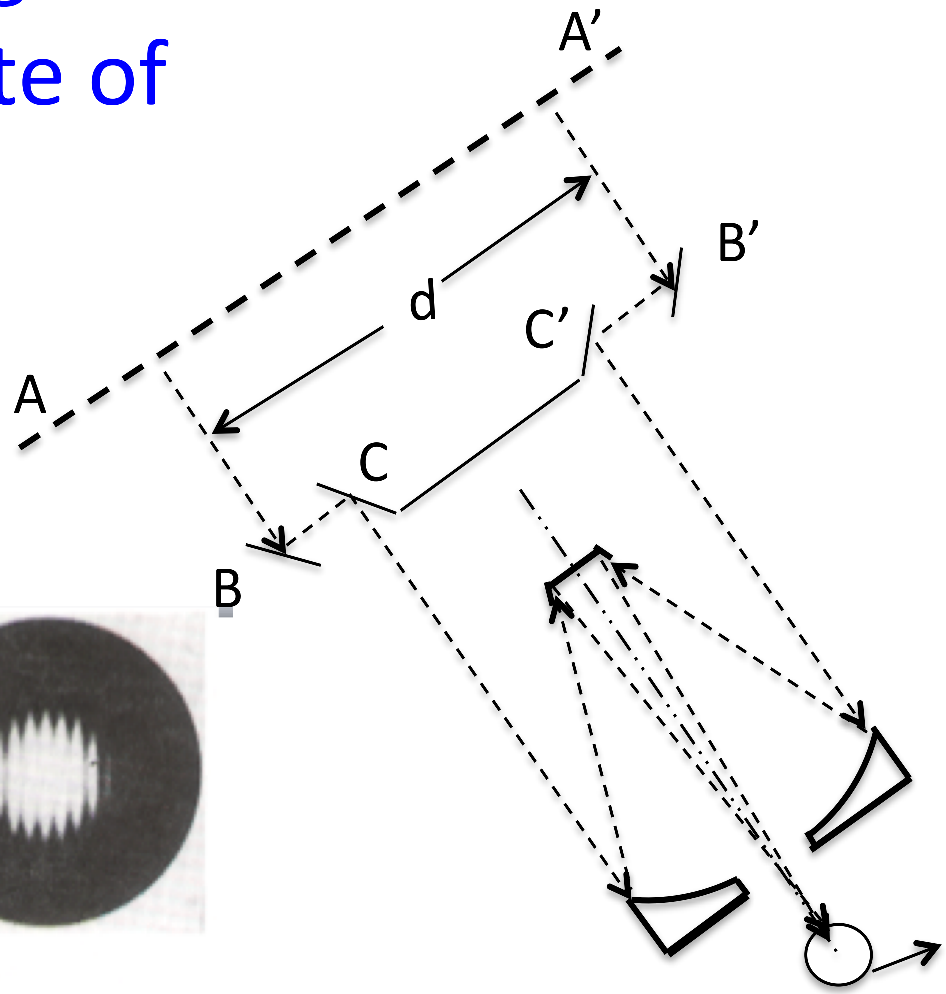


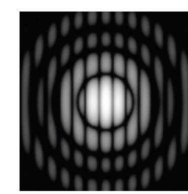


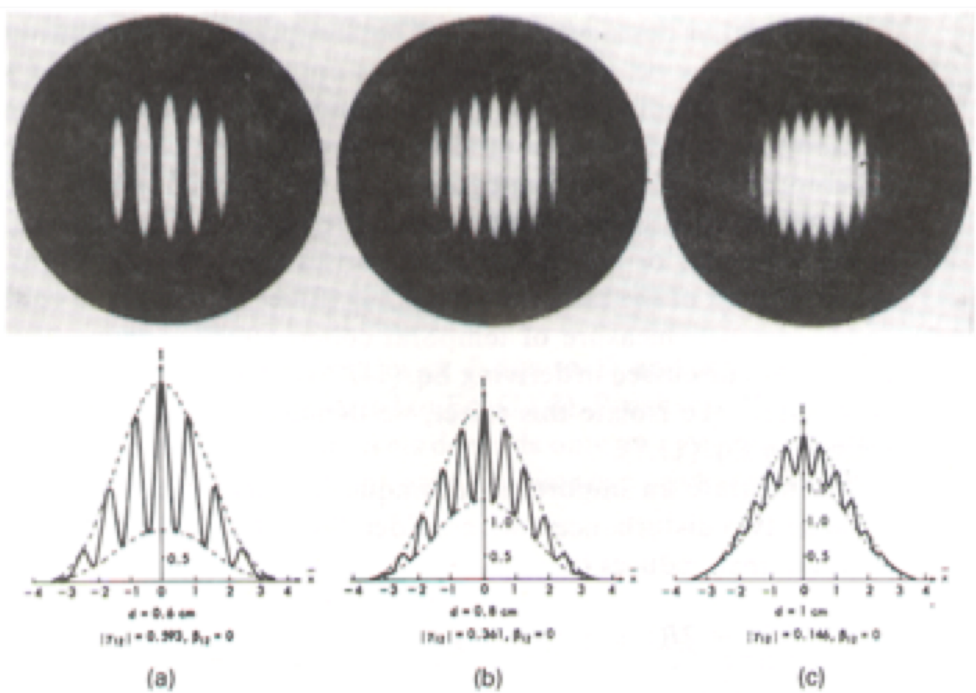
- If the light from P_1 is polarized orthogonal (linear or circular) to light from P_2
  - Fringes under the dotted curve disappear
  - Light from P_1 is no longer correlated with light from P_2
    - P_1 and P_2 both remain independent white light sources
    - The intensity on the screen is the LINEAR superposition of the patterns

Interferometer fringe contrast depends on the state of polarization of the two beams

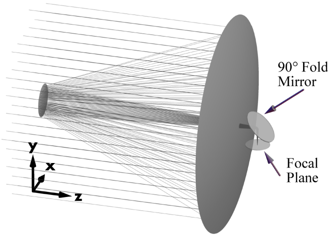








Michelson stellar interferometer

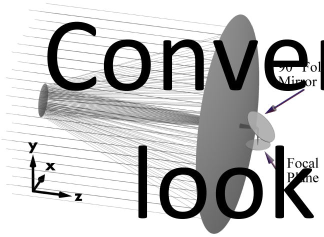


Mitigation Phase plate

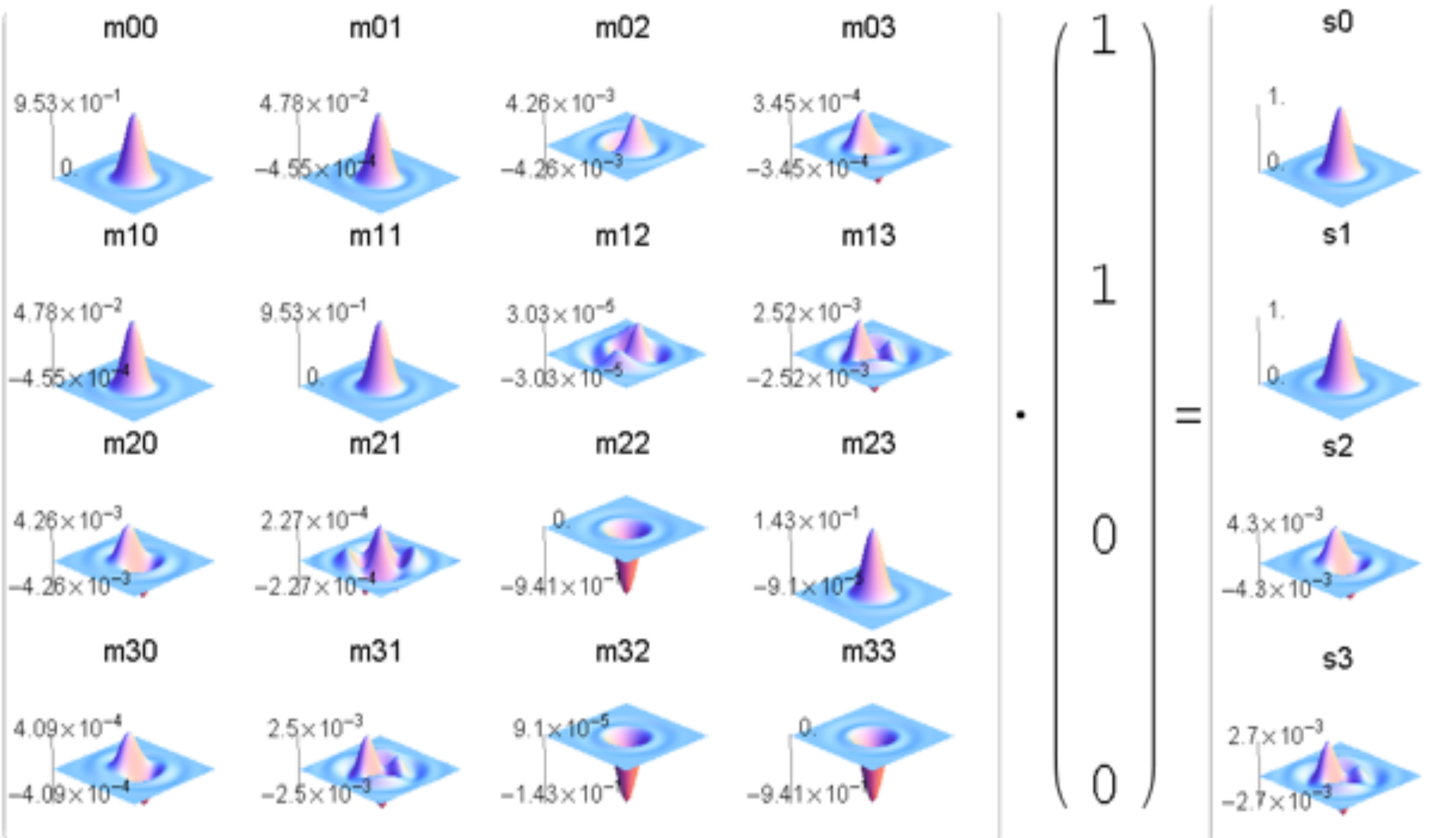
$$\mathbf{J}_{\mathrm{T+Cgph}} = \begin{pmatrix} J_{XX} & J_{YX} \\ J_{XY} & J_{YY} \end{pmatrix} \equiv \begin{pmatrix} A_{XX}\, e^{i\phi_{XX}} & A_{YX}\, e^{i\phi_{YX}} \\ A_{XY}\, e^{i\phi_{XY}} & A_{YY}\, e^{i\phi_{YY}} \end{pmatrix}$$

To minimize the polarization effects, we need to develop a corrective optical element whose Jones pupil, $\mathbf{J}_{\mathrm{corrector}}$ has the property:

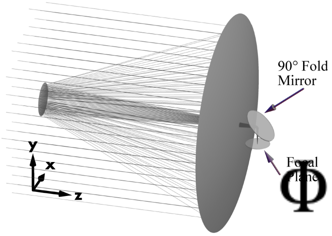
$$\mathbf{J}_{\mathrm{System}} = \left(\mathbf{J}_{\mathrm{T+Cgph}}\right) \cdot \left(\mathbf{J}_{\mathrm{Corrector}}\right) = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

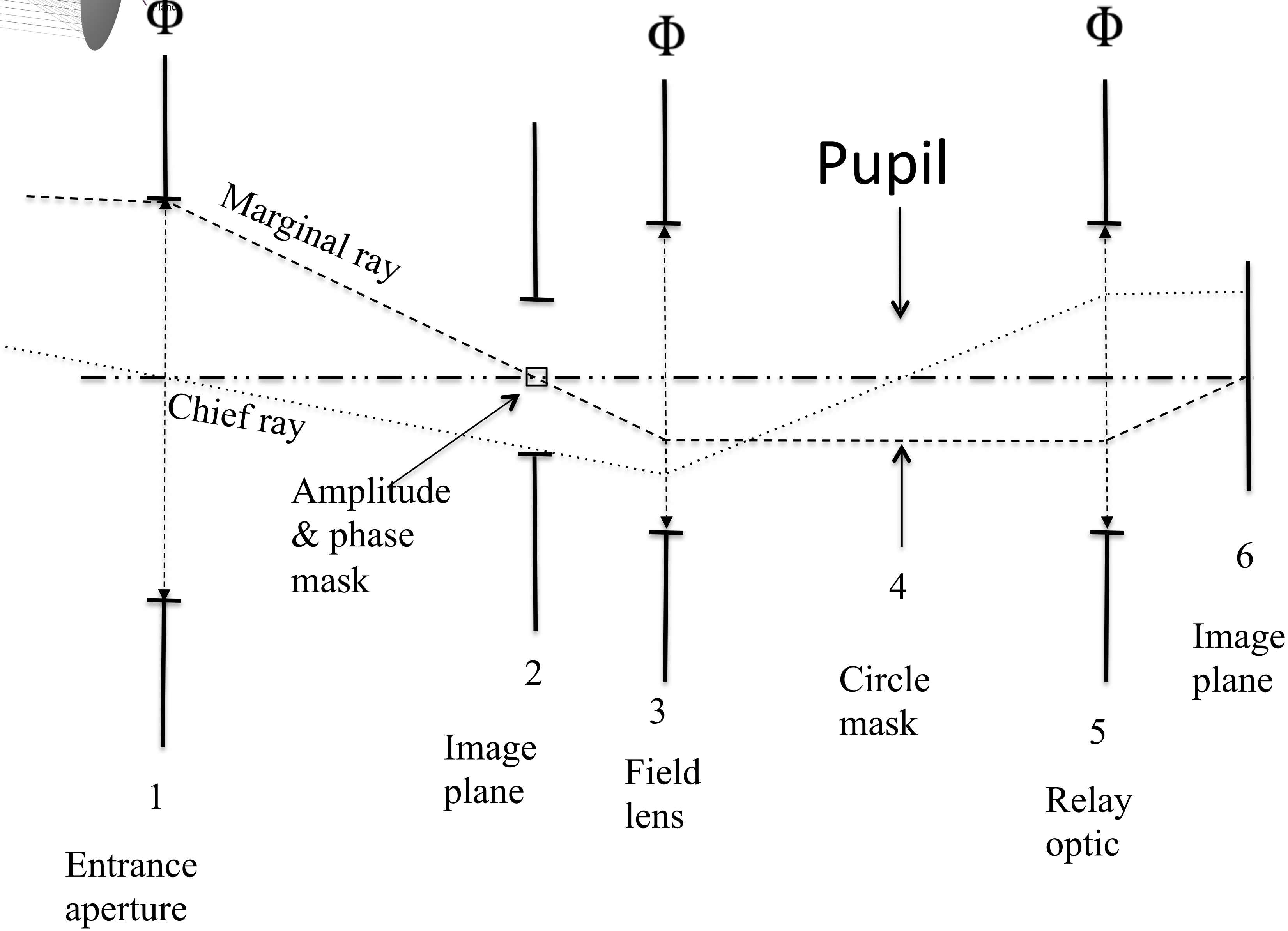


Convert the ARM to a Mueller Matrix and look at x-polarized light Stokes vector

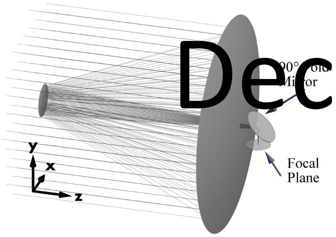


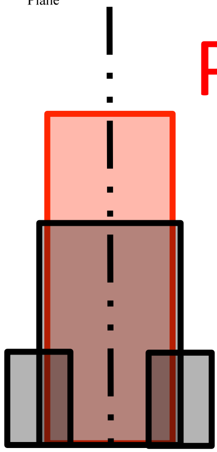
Schematic coronagraph





Decomposition of power in the PSF





$PSF_{diffraction}$ ← Assumes no elements that polarize (perfect-reference)

$PSF_{Unpolarized}$

PSF_p PSF_s

} Measured at the focal plane

$PSF_{Unpolarized} = PSF_{diffraction}$ -absorbed & redirected energy

$PSF_{measured} = PSF_{Unpolarized} + PSF_s + PSF_p$

- As more fold mirrors are added the PSF unpolarized drops and the s and p PSF's grow.
- As the aperture grows larger, but the # of fold mirrors stays the same, PSF unpolarized gets narrower relative to the s and p PSFs. Therefore at large apertures the polarization PSFs will dominate.
- The cross-product PSF's are not shown because they are off-scale on this drawing.