Space astronomy
Spectrometers & Polarimeters - Polarization aberrations

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Spectrometers: Grating; Prisms; Fourier Transform Spectrometers

NASA flight opportunities for small instruments

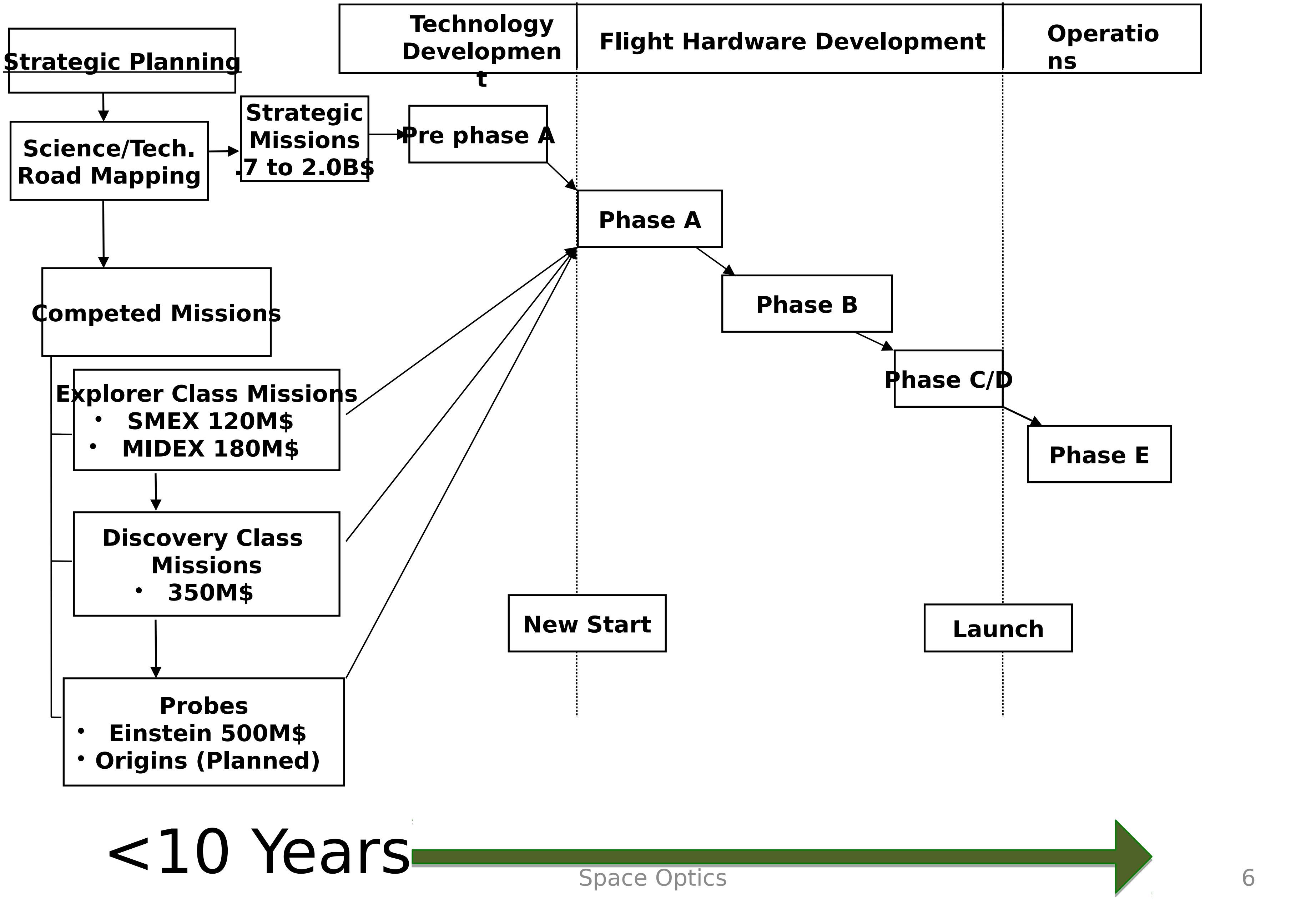
- SMEX
- EXPLORER
- Probes
- Large missions
  - LUVOIR
  - HabEx

TRL #	Definition	Description	Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental-proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Documented analytical/experimental results validating predictions of key parameters.

TRL #	Definition	Description	Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments	Documented test performance demonstrating agreement with analytical predictions.
5	Component and/or breadboard validation in relevant environment.	Invention begins, practical application is identified but is speculative.	Documented description of the application/concept that addresses feasibility and benefit.
6	System/sub-system model or prototype demonstration in an operational environment. .	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment	Documented test performance demonstrating agreement with analytical predictions.

TRL #	Definition	Description	Criteria
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	Documented description of the application/concept that addresses feasibility and benefit.
9	Actual system proven through a successful mission operations/	The final product is successfully operated in an actual mission.	Documented mission operational results

NASA Astronomy and Physics Mission Flow



The next 50 years of space astrophysics

- **Far IR Surveyor** – The Astrophysics Visionary Roadmap identifies a Far-IR Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.
- **Habitable-Exoplanet Imaging Mission** – The 2010 Decadal Survey recommends that a habitable-exoplanet imaging mission be studied in time for consideration by the 2020 decadal survey.

The next 50 years of space astrophysics

- **Large UV/Optical/IR Surveyor** –The Astrophysics Visionary Roadmap identifies a Large UV/Optical/IR Surveyor with improvements in sensitivity, spectroscopy, high contrast imaging, astrometry, angular resolution and/or wavelength coverage. The 2010 Decadal Survey recommends that NASA prepare for a UV mission to be considered by the 2020 decadal survey.
- **X-ray Surveyor** – The Astrophysics Visionary Roadmap identifies an X-ray Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.

Habitable ExoPlanet **Imaging** Mission

- Primary science goals: Direct imaging of Earthlike planets & Cosmic origins science enabled by UV capabilities
- ExoEarth detection and characterization requirements:
  - ~**10^{-10} contrast** **Today's Lecture**
  - **Coronagraph and/or starshade**
  - Optical and near-IR camera for planet detection and characterization
  - IFU, R>70 spectrum of 30 mag exoplanet
  - 1 arc-second FOV

UV/Optical/IR Surveyor

- **Primary science goals**:
  - Direct imaging of Earthlike planets
  - Search for bio-signatures
  - Broad range of cosmic origins science
- **Cosmic Origins Science requirements:**
  - HST-like wavelength sensitivity (FUV to Near-IR)
  - Suite of imagers/spectrographs, properties to be determined.

Innovative telescope primaries

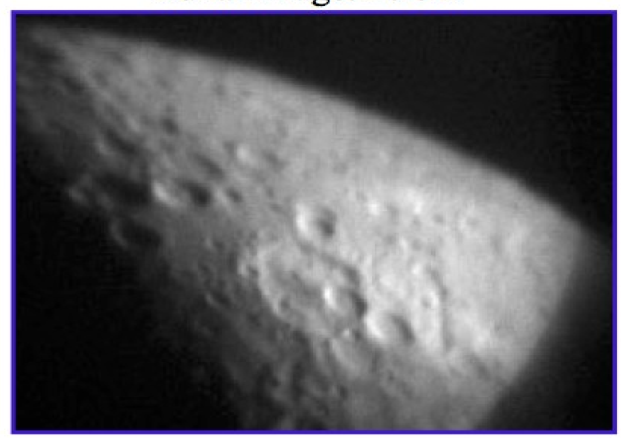
- How to achieve 1 kg/m^2 (JWST is 50kg/m^2)
  - Including back-up structure
- Capable of > 300 $meter^2$ surface area
- Cost effective “mass” production of the telescope
- Solution we spoke about last week was to launch the primary in segments
- Another candidate is to launch a gossamer mirror

Membranes are not new

- Eyeglass [Hyde, Dixit & Early, 1998-2005]
  - 5 meter, segmented deployable glass micro-sheet membrane diffractive optical element (DOE) with achromatic corrector
- Early, Hyde, Baron *Twenty meter space telescope based on diffractive Fresnel lens*, Proceedings SPIE **5166**, 2004
  - Obtained first astronomical image

5 meter membrane

Lunar image: 20 cm

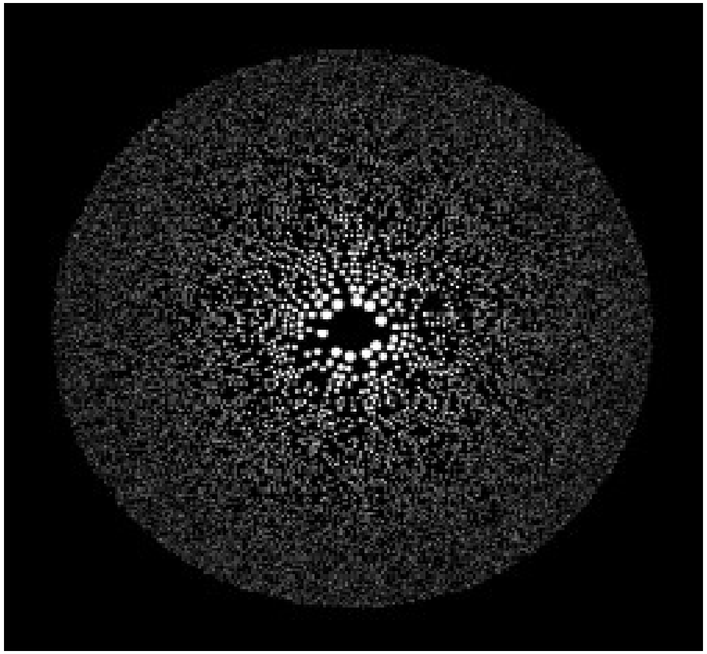


Baron

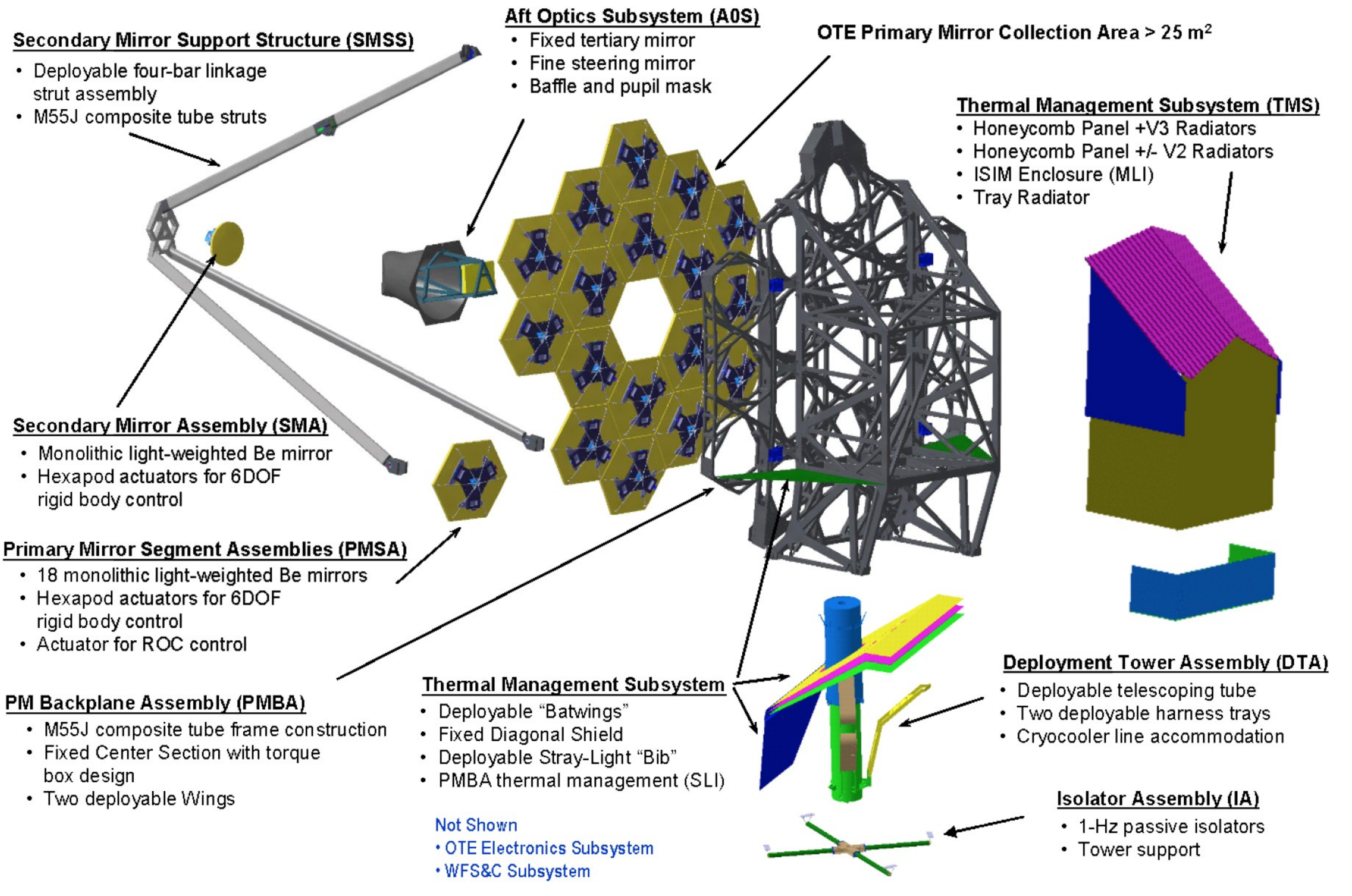
- P. Atcheson (2012)
  - Fabrication and design issues for membrane collectors

Photon Sieve membrane

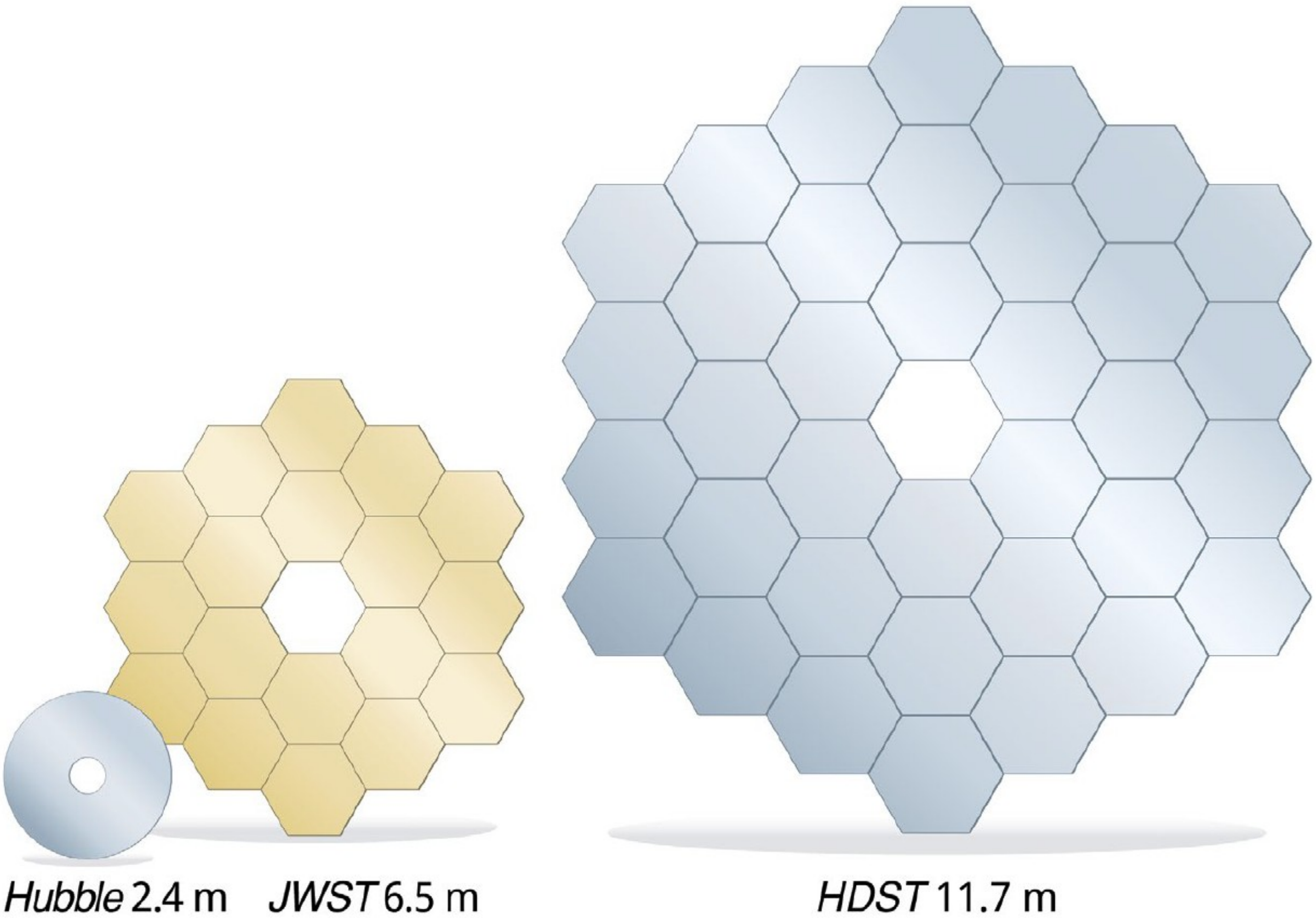
- Precision (diameter and location) holes in an opaque membrane
- System challenges
  - Holes are very small ~ λ $\alpha\tau$ the edge of the pupil
  - Poor transmittance
  - Image quality strongly dependent on bandwidth => monochromatic applications
- Applications: solar astrophysics emission spectra (Falcon Sat 7 flight science @ SPIE 8442-45, G. Anderson)



JWST


Secondary Mirror Support Structure (SMSS)
• Deployable four-bar linkage strut assembly
• M55J composite tube struts
Aft Optics Subsystem (A0S)
• Fixed tertiary mirror
• Fine steering mirror
• Baffle and pupil mask
OTE Primary Mirror Collection Area > 25 m2
Thermal Management Subsystem (TMS)
• Honeycomb Panel +V3 Radiators
• Honeycomb Panel +/- V2 Radiators
• ISIM Enclosure (MLI)
• Tray Radiator
Secondary Mirror Assembly (SMA)
• Monolithic light-weighted Be mirror
• Hexapod actuators for 6DOF rigid body control
Primary Mirror Segment Assemblies (PMSA)
• 18 monolithic light-weighted Be mirrors
• Hexapod actuators for 6DOF rigid body control
• Actuator for ROC control
PM Backplane Assembly (PMBA)
• M55J composite tube frame construction
• Fixed Center Section with torque box design
• Two deployable Wings
Thermal Management Subsystem
• Deployable "Batwings"
• Fixed Diagonal Shield
• Deployable Stray-Light "Bib"
• PMBA thermal management (SLI)
Not Shown
• OTE Electronics Subsystem
• WFS&C Subsystem
Deployment Tower Assembly (DTA)
• Deployable telescoping tube
• Two deployable harness trays
• Cryocooler line accommodation
Isolator Assembly (IA)
• 1-Hz passive isolators
• Tower support

Scaled up JWST

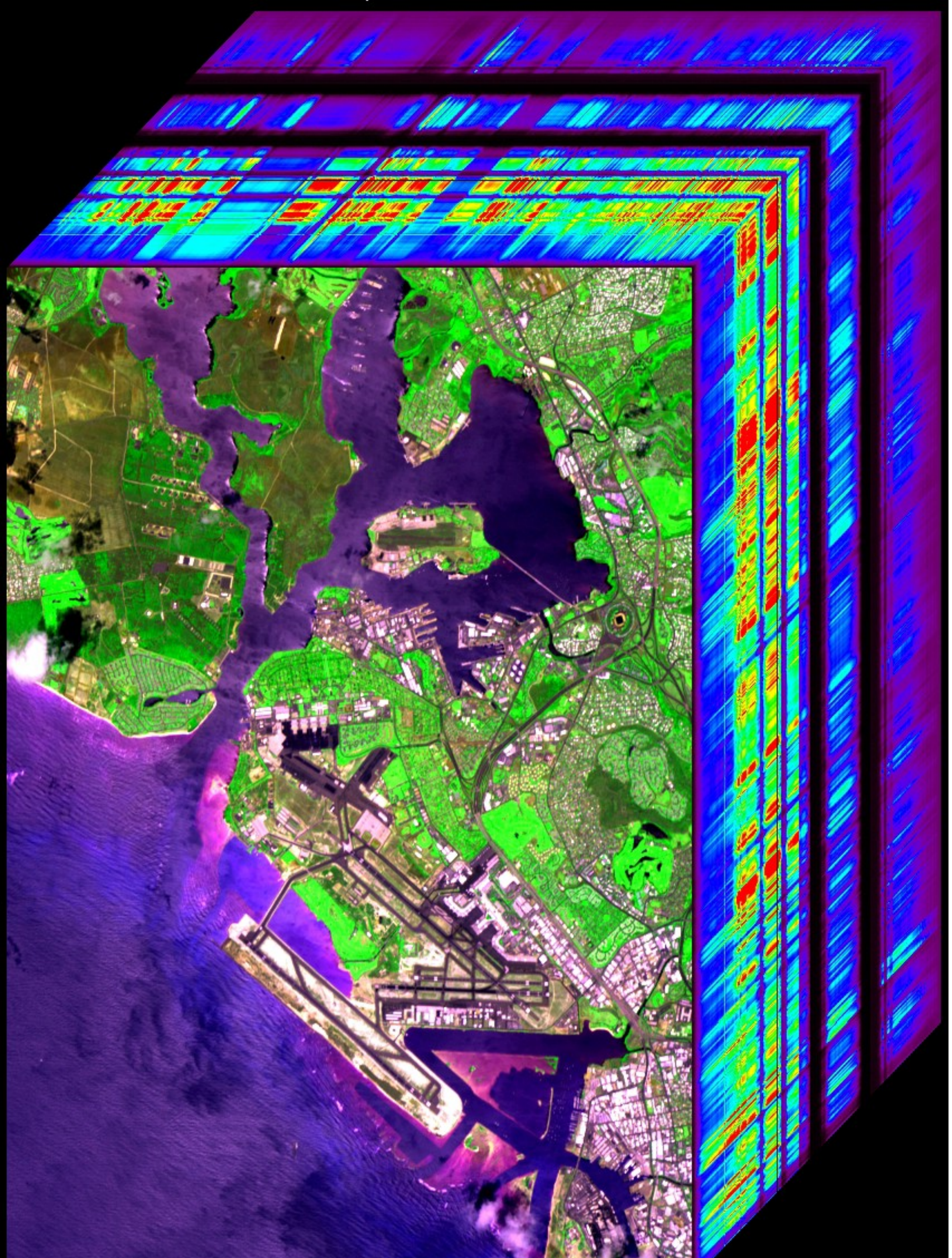


Future science instruments

- Internal Coronagraph with visible-near-IR IFU (400 nm–2 microns), FOV 10'', 10^{10} starlight suppression, 35 milliarcsec inner working angle (3 λ/D at λ = 550 nm, D = 12 m).
- UV Integral Field Spectrometer (90–300 nm), FOV 1'–3', R ≤ 100,000.
- Visible Imaging Array (300 nm–1 micron), FOV 6', Nyquist sampled at 500 nm.
- Near-IR imager and spectrograph (1 micron–2 microns), FOV 4', Nyquist sampled at 1.2 microns.
- Multi-object spectrograph (350 nm–1.6 microns), FOV 4', R ≤ 2000.
- Mid-IR imager (2.5 microns–5 microns)

Topics in space instrument design

- Imaging spectrometers for planetary science
  - Thermal-mechanical stability
  - A-thermalize optical systems
- Fourier transform spectrometers
  - Extended sources
  - High $A\Omega$ Wide spectral bandpass
  - High spectral resolution
  - Challenges to fly one of these
    - Vibration [OPD maps into time]



Imaging spectrometers

Pearl harbor, Hawaii

Scanning grating spectrometer

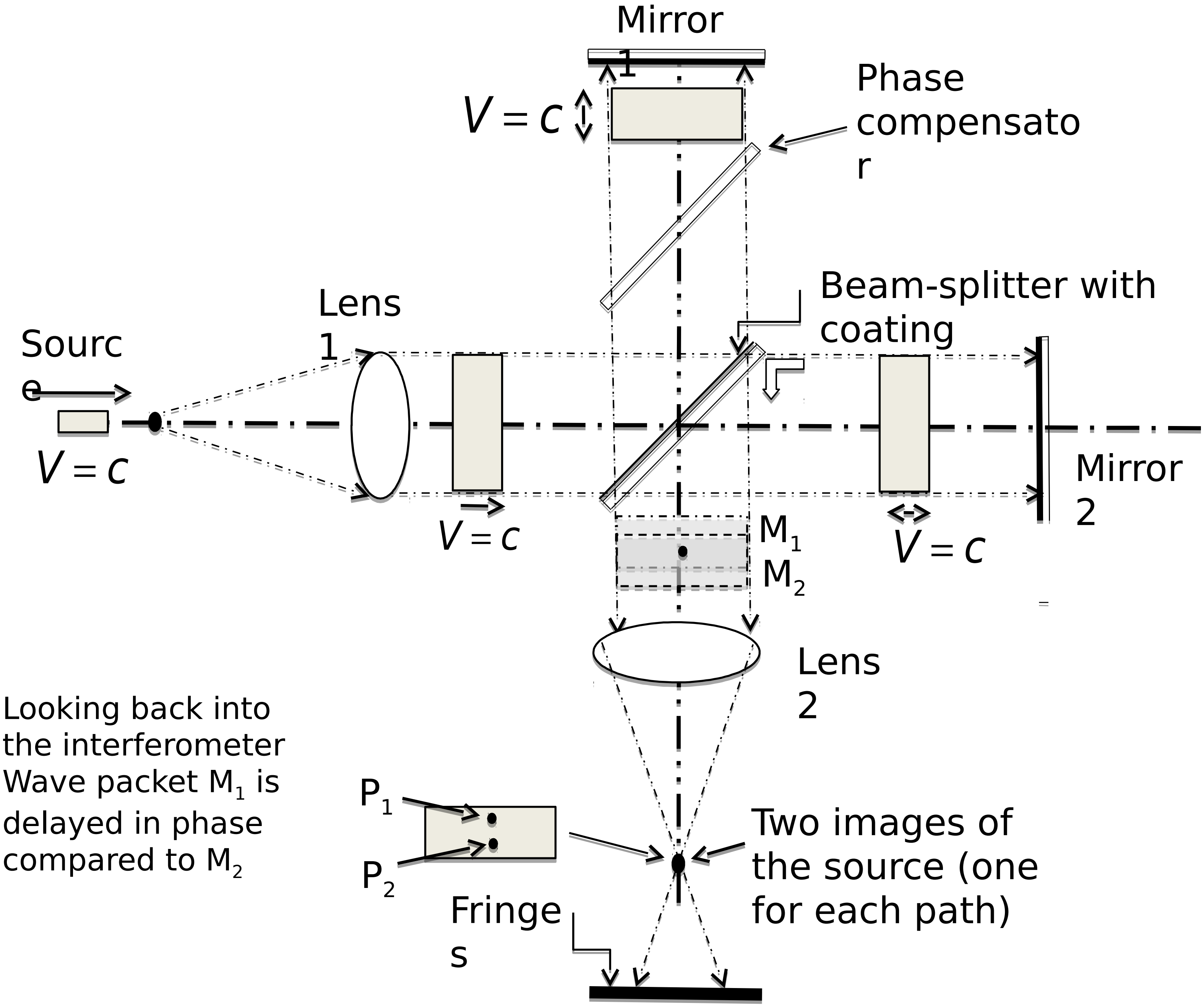
Spectral Range

370 to 2500 nm

Sampling 9.8 nm

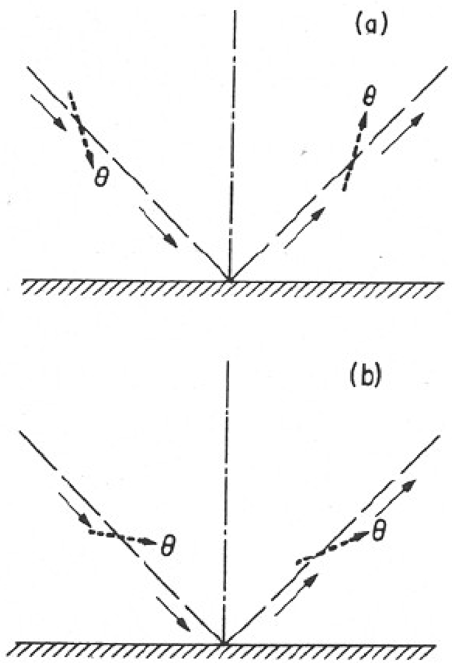
Accuracy 0.5 nm

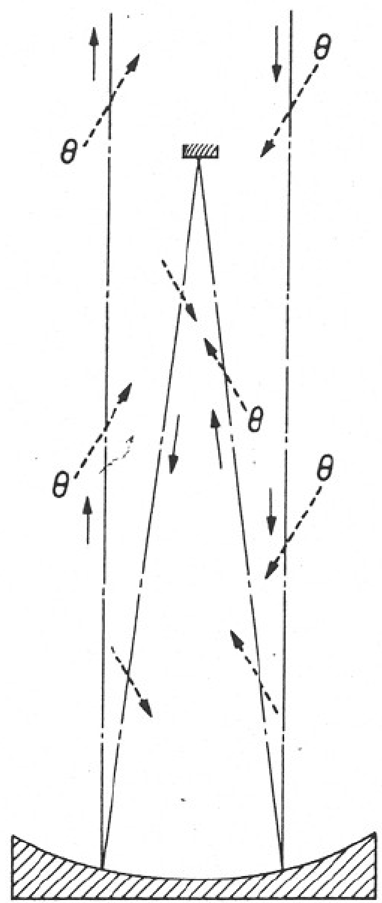
Fourier Transform Spectrometer

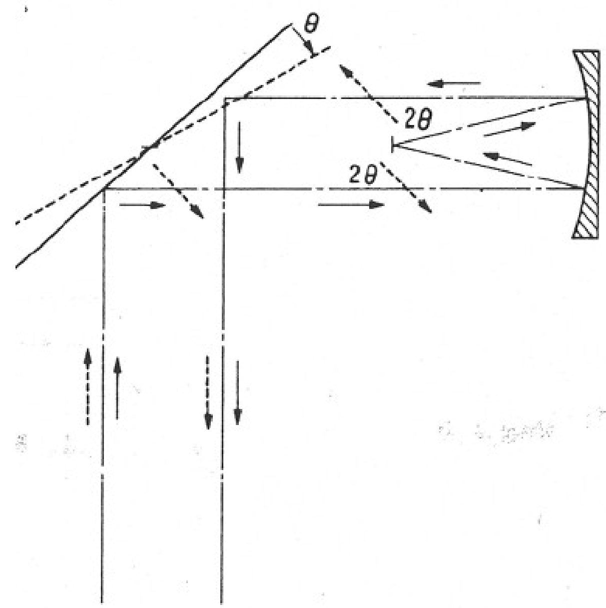


Looking back into the interferometer Wave packet M_1 is delayed in phase compared to M_2

Mirror tilt analyses



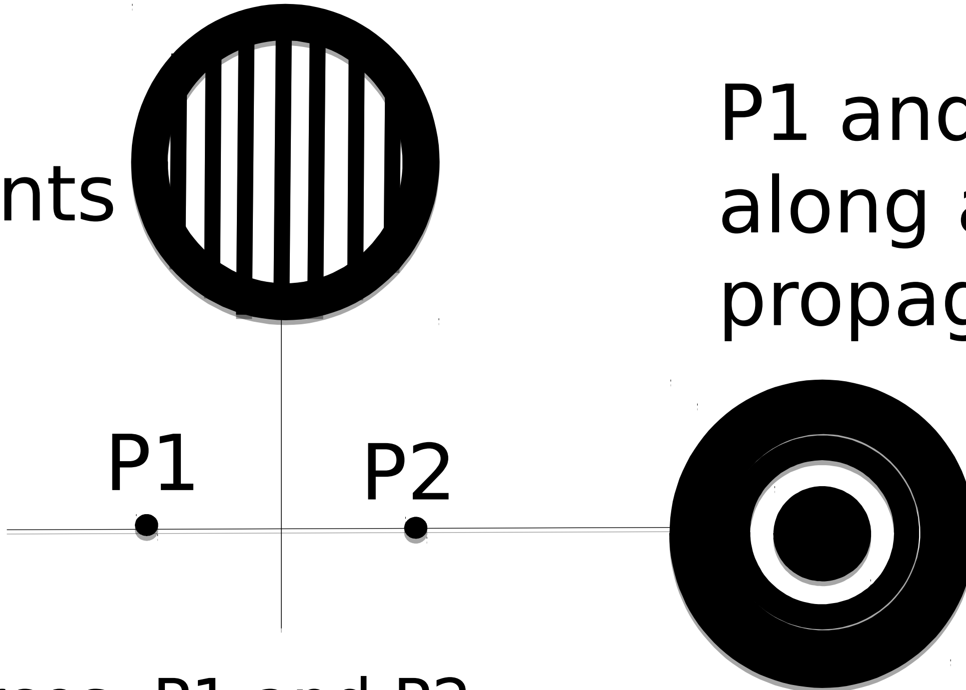




Straight line and curved fringes

Tilted wavefronts

P1 and P2 aligned along axis of propagation



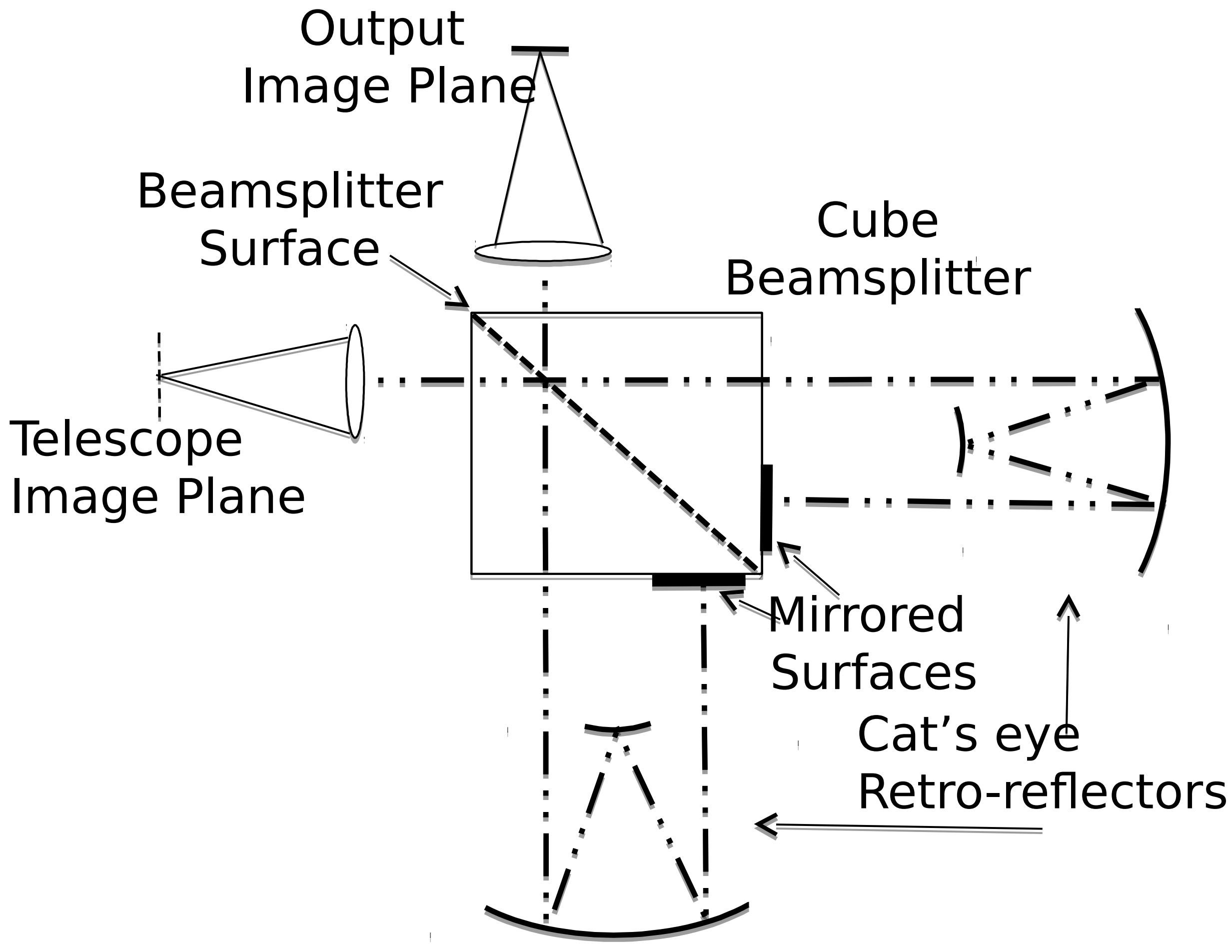
Two point sources, P1 and P2.

P1 is images through arm 1 of the interferometer &

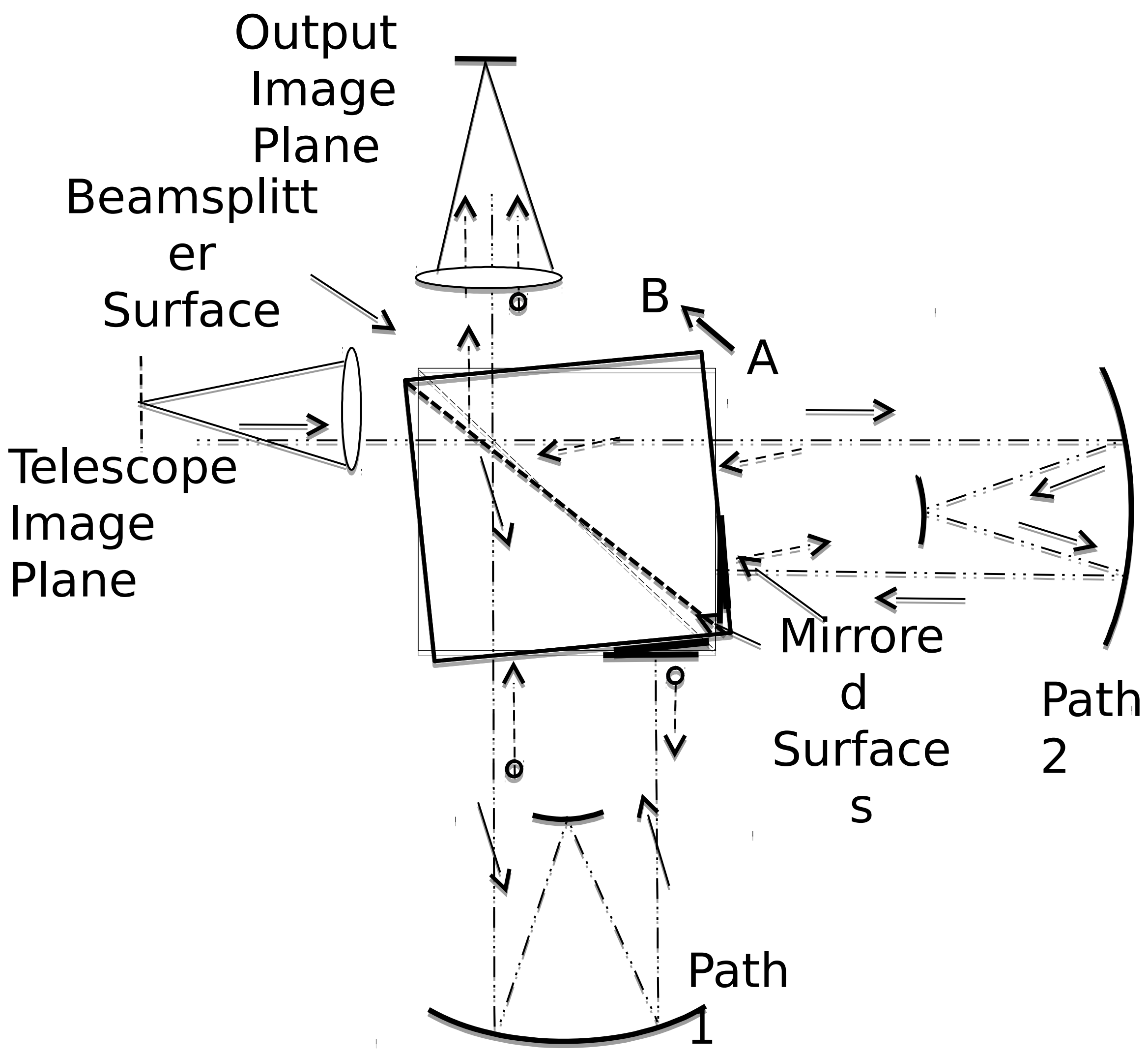
P2 is imaged through arm 2 of the interferometer

Vibration shakes the fringes need tilt compensation to hold alignment in space

Tilt compensated FTS



Tilt compensated FTS



Fringe contrast =f(tilt)

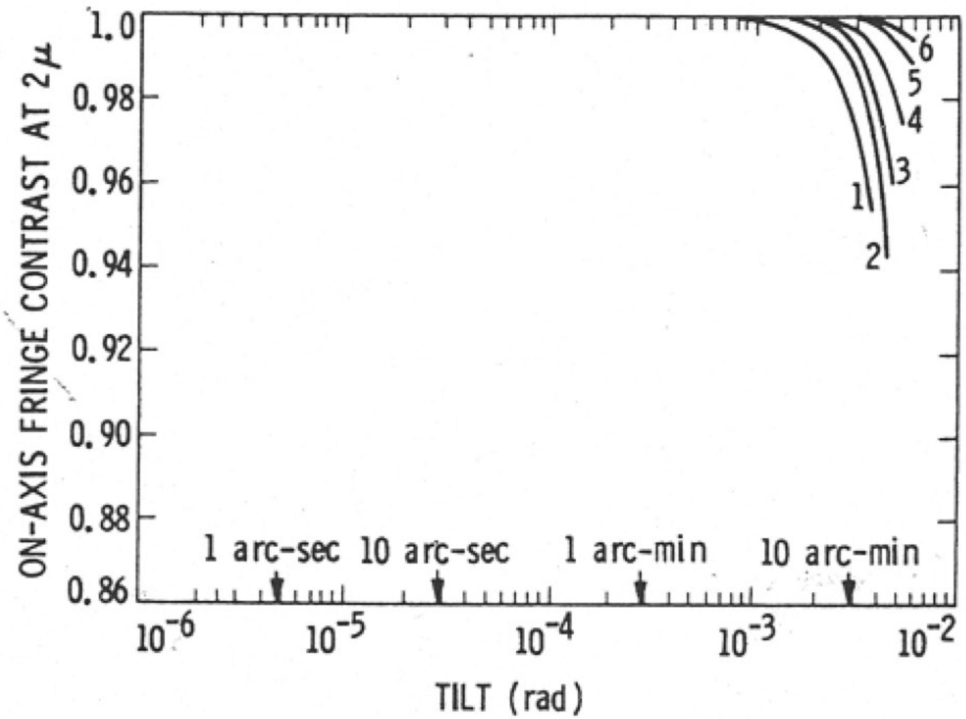


FIG. 2.33. Plot of on-axis fringe contrast at 2 μ as a function of tilt in radians for tilts of (1) the retroflat, (2, 3) bending flats, (3, 4) beam splitter y and x, and (5, 6) cat's-eyes. Graph shows that the interferometer components can be tilted (misaligned) to at least one arc-minute with insignificant effect on the on-axis fringe contrast.

Polarization Aberrations in Astronomical Telescopes:
The Point Spread Function

J. B. Breckinridge

The space environment should enable “perfect” imaging

But your optics get in the way!

Why is polarization of interest?

- Planet & earth measurements
  - Atmospheric composition & chemistry
  - Aerosol scattering
  - Radiation budget
  - Surface (texture, solid & liquid)
- ExoPlanet polarization measurements
  - Orbital elements
  - Atmospheric composition & chemistry
  - Dust, gas & formation in protoplanetary systems

Your optics get in the way

- Telescope & instrument internal polarization
  - **Measurement errors for both polarized and unpolarized sources**
  - Reduces contrast & SNR
  - Complicates calibration
  - Contrast of 10^{-7} may be impossible
  - Astrometric errors ~ 5 msec.
- Sources of errors
  - **Polarization & geometric aberrations**
  - **Vector-wave interaction of light and matter**

Modern astronomical telescopes --

- Partially polarize wavefronts as they propagate through the telescope and instrument to the focal plane
- This physical optics phenomenon modifies the shape & polarization content of the PSF at all points across the FOV.
- Optical design of high fidelity systems need to be optimized for polarization aberrations
  - Exoplanet coronagraphs
  - Precision astrometric instruments
  - Precision radiometers & spectrometers

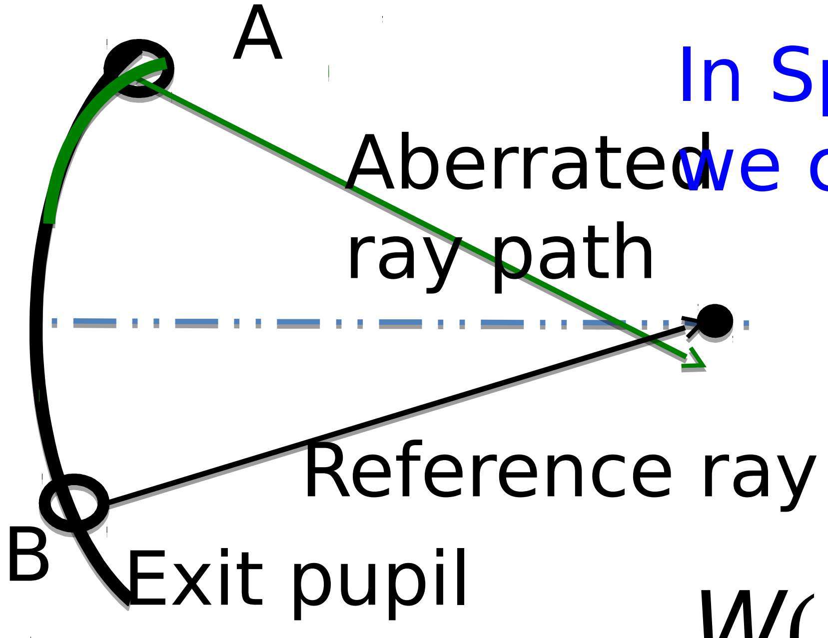
For 50 years we have been calibrating telescopes for photo-polarimetry

- To measure $\{I, Q, U, V\}$ of objects
  - stars, interstellar matter, planets, nebulae, galaxies, quasars, etc.
  - Phenomenological calibration
- Here we will show that polarization also plays a major role in hi fidelity image formation
  - Physical understanding of error sources => we can control & mitigate them!

Geometric aberrations

$$\text{Wavefront error}\left(W\right)=\frac{\text{reference ray path}-\text{ray path}}{\lambda}=\frac{\text{OPD}}{\lambda}$$

For all points *x*,*y* across the exit pupil



In Space, with no atmosphere, we can come close to

$$W(x,y)=0$$

But . . .

$$W(x,y)=0 \neq> \text{perfect image}$$

Need to examine polarization aberrations

Geometric & Polarization Aberrations

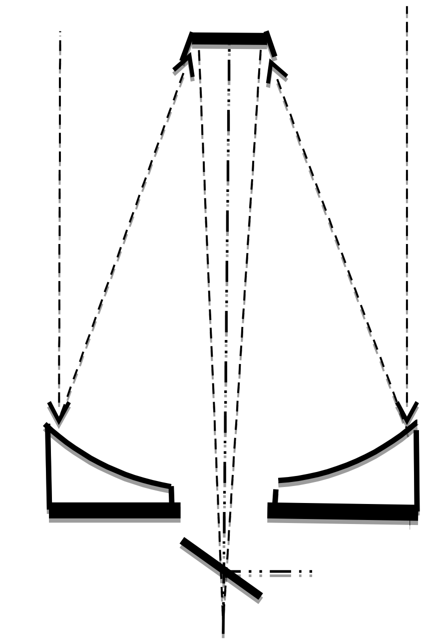
It is easy to visualize surface OPD geometric

Challenge to visualize polarization aberrations

Complex vector wavefronts are retarded (phase) and absorbed (amplitude)

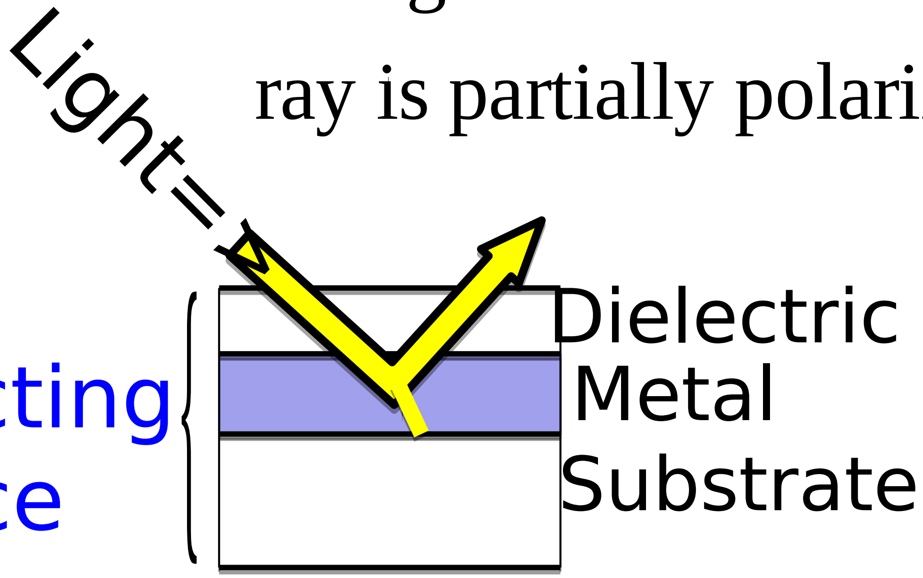
Source of polarization aberrations

- **Astronomical telescopes require metal mirrors for broad-band high reflectivity**
- Reflection from metal mirrors =>



Both amplitude and phase change & the reflected ray is partially polarized

Reflecting surface



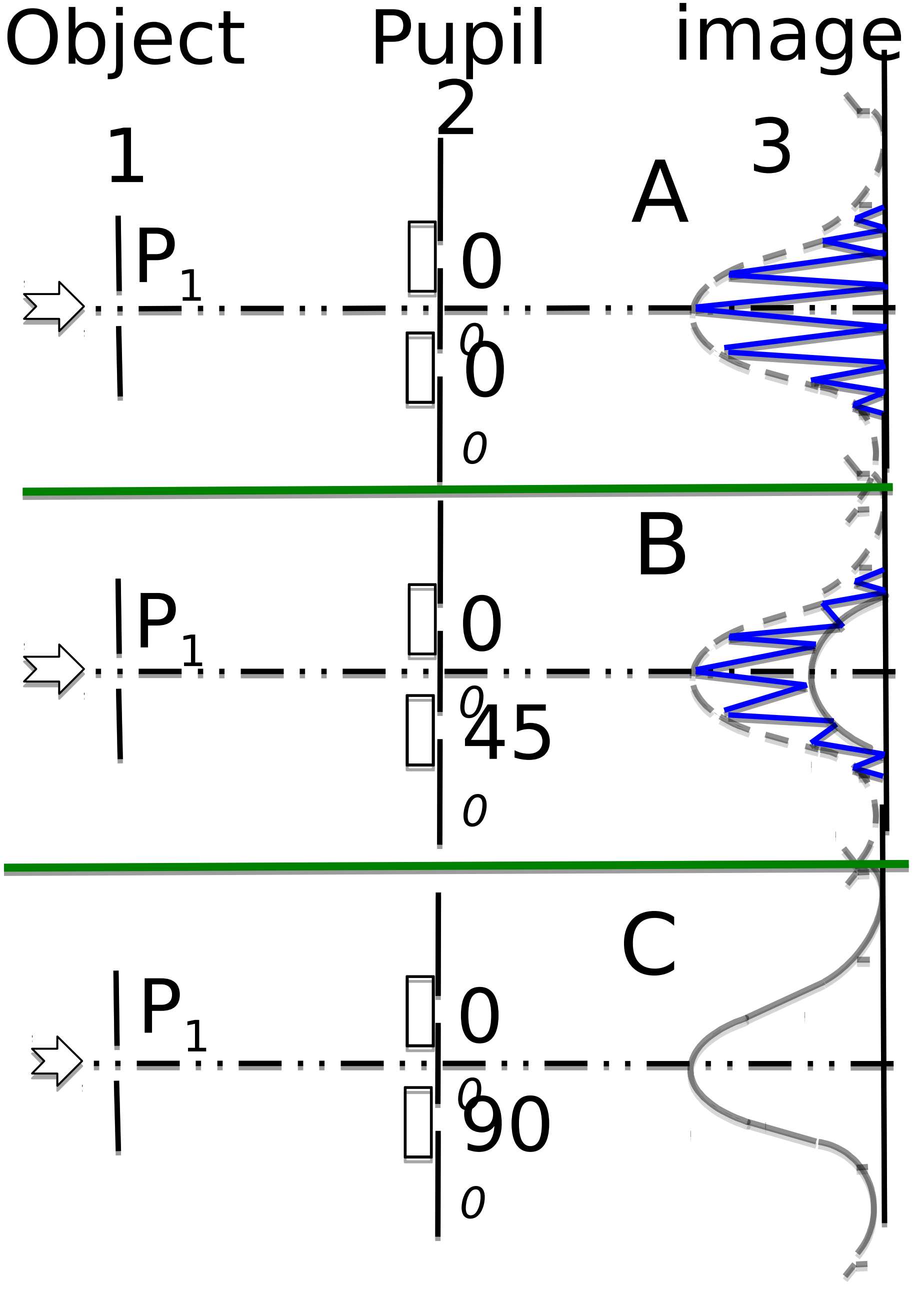
Comment

- What happens when partially polarized beams combine?
  - Less contrast in the image
  - Higher noise
  - Lower signal
- Polarization refers to an intensity measurement
- Underlying "polarization" is the vector wave nature of light
  - Vectors expressed in terms of complex numbers (amplitude and phase)

$$I = \left|A + i\phi\right|^2 \text{ or } I = \left|Ae^{-i\phi}\right|^2 = \sum_{n=1}^{n=N} \left|A_n(x,y)\exp(i\phi_n(x,y))\right|^2$$

$$\text{if coherent then } I = \left|\sum_{n=1}^{n=N} A_n(x,y)\exp(i\phi_n(x,y))\right|^2$$

Double slit: coherence & image quality

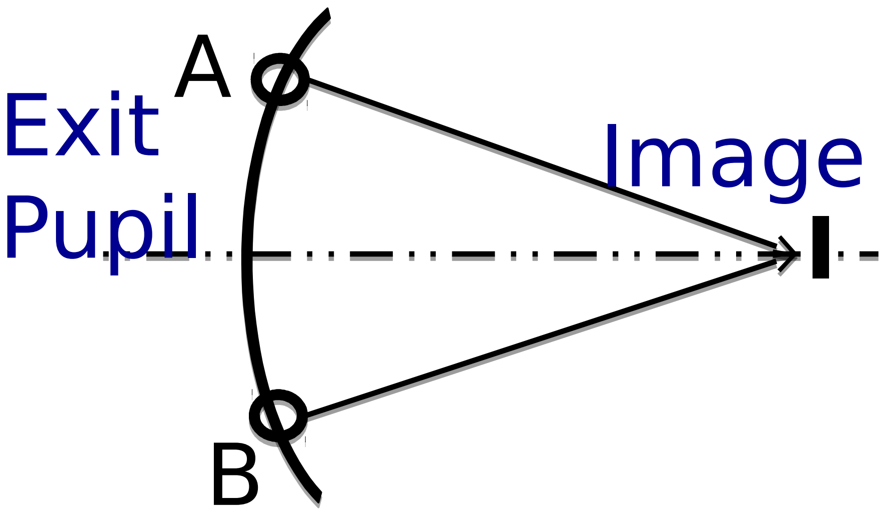


The intensity in plane 3 results from a point source in object space and is therefore a PSF

Polarization aberrations

Polarization determines image quality.

- Even though the geometric wavefront error W=0.0
- E & M fields from regions A and B need to be correlated (the SAME polarization state) to fully illuminate the pixels in an image



A simple experiment shows this } =>

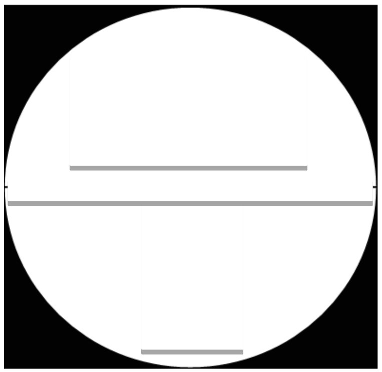
Role of vector waves in image formation

For zero OPD error *W(x,y)*=0.0

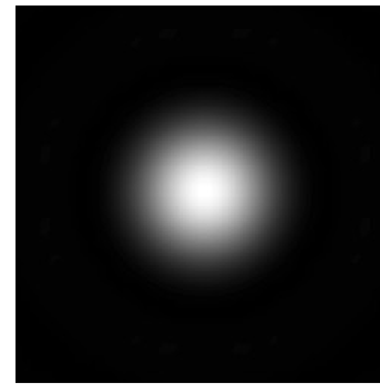
Exit pupil

Image plane PSF

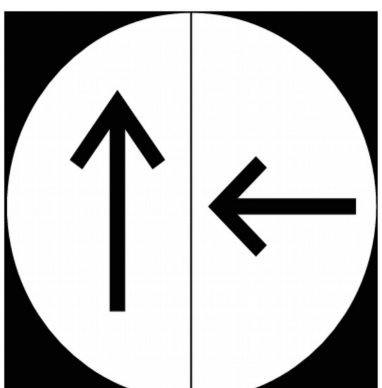
No Polarizer



Resolution is position angle **<u>in</u>**dependent

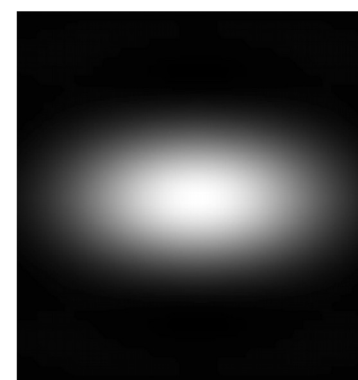


To represent internal polarization in the extreme we add two perpendicular linear polarizers



Resolution is position angle **<u>de</u>**pendent

The PSF is the incoherent sum of two “D” apertures



Observations

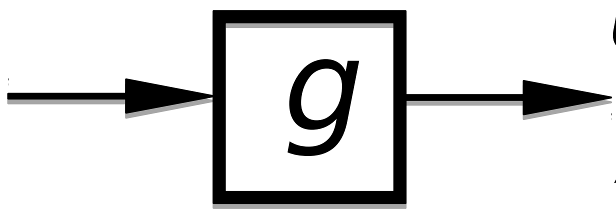
- Orthogonally polarized light does not interfere to to contribute to an image.
- The shape of the point spread function depends on how polarization changes across the exit pupil.

Questions?

- What are the sources of instrument polarization in astronomical telescopes?
- What is the magnitude of the effect?
- What is the impact?

Assume the optical system is represented by a system that is linear in complex **scalar** amplitude and phase

$$U_{IN} = A_{IN} e^{i\phi_{IN}}$$



$$U_{OUT} = A_{OUT} e^{i\phi_{OUT}}$$

- Amplitudes $[A]$ are multiplied
- Phases ϕ are added

Classical Scalar Diffraction

Propagate the **field** through the system to find the **complex scalar field** at the focal plane $U_3\left(x_3, y_3\right)$

Pupil $\tau_2\left(\xi_2, \eta_2\right)$
Plane 2

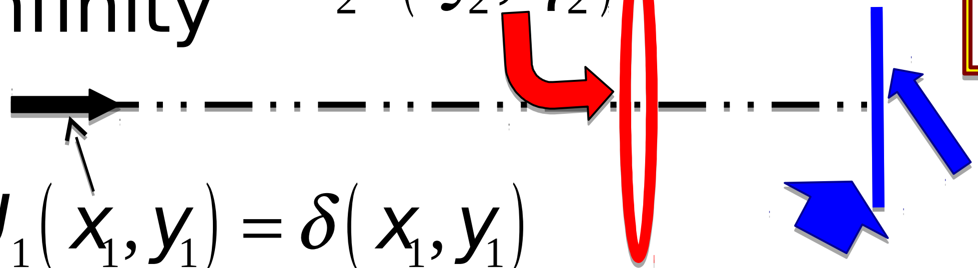
Image Plane 3

x, y : image plane

ξ, η : pupil plane

Star at infinity

$U_2^-\left(\xi_2, \eta_2\right)$



$U_1\left(x_1, y_1\right) = \delta\left(x_1, y_1\right)$

$I_3\left(x_3, y_3\right) = \left|U_3\left(x_3, y_3\right)\right|^2$

$$U_3\left(x_3, y_3\right) =$$

$$\mathrm{K}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[U_2^-\left(\xi_2, \eta_2\right)]\times\tau_2\left(\xi_2, \eta_2\right)\times\exp\left\{-j\frac{2\pi}{\lambda f}\left(x_3,\xi_2 + y_3,\eta_2\right)\right\}d\xi\, d\eta$$

Where $\tau_2\left(\xi_2, \eta_2\right) = A_2\left(\xi_2, \eta_2\right) + i\phi_2\left(\xi_2, \eta_2\right)$

Comment

- But we have seen that polarization plays a role in image formation
- Therefore we need a mathematical formalism that uses vectors of complex numbers to describe image formation in partially polarized light.
- The full mathematical formalism requires statistical optics and theories of partial coherence given by Mandel & Wolf (1965) Rev. of Mod Phys **37**, 231-285 & Goodman (2015) Statistical Optics

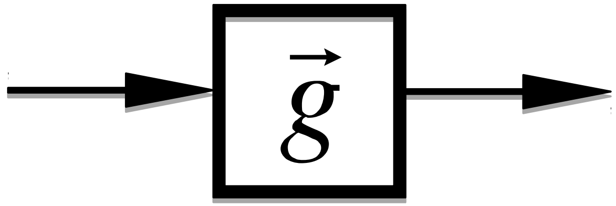
Decompose white-light (star) into its polarization components

- **We select any orthonormal polarization component basis set for ray trace**
- Select the easiest for for intuition
- Component perpendicular ($\perp$, or X or s) **&**
- Component parallel ($\parallel$, or Y, or p)

Assume the optical system is represented by a system that is linear in complex **vector** amplitude and phase

Thermal white-light

$$\vec{U}_{IN} = \left[A_{IN}e^{i\phi_{IN}}\right]_{\perp} + \left[A_{IN}e^{i\phi_{IN}}\right]_{\|}$$



$$\vec{U}_{OUT} = \left[A_{OUT}e^{i\phi_{OUT}}\right]_{\perp,\perp} + \left[A_{OUT}e^{i\phi_{OUT}}\right]_{\|,\|} + \left[A_{OUT}e^{i\phi_{OUT}}\right]_{\perp,\|} + \left[A_{OUT}e^{i\phi_{OUT}}\right]_{\|,\perp}$$

Need terms that allow for cross products

Comment

- The transfer function $\vec{g}$ is related to the well-known Mueller matrix or to the Jones matrix.
- The Jones & Muller representations will be used later.

How do we evaluate $\vec{g}$?

- Recognize that unpolarized white-light can be represented by 2 orthogonal polarized eigen- states
- Propagate the E & M field through the optical system
  - Transmits dielectrics
  - Reflects from metals & dielectrics
  - Interacts with masks and stops
  - Free space propagation
  - Diffracts

Electric field across the exit pupil

- Each single ray traced through the system is mapped into 4 complex points at at a single point in the exit pupil.
- For the amplitude of the light polarized in the *X* direction into the system, we measure the amplitude out of the system in the *X* direction and call this A_{XX}
- For the phase of the light polarized in the *X* direction into the system, we measure the amplitude out in the *X* direction and call this ϕ_{XX}
- Therefore we denote the field at one of these 4 complex points as

$$A_{XX}\, e^{i\phi_{XX}}$$

And we represent the amplitude and phase at point ξ,η in the exit pupil using the shorthand notation:

$$A(\xi,\eta)_{XX}\, e^{i\phi(\xi,\eta)_{XX}} = J_{XX}$$

Comment

- The telescope & instrument is the linear operator

For a single complex field point in object space the ray is mapped through the optical system, to find

White-light source

$$\left.\begin{array}{l} U_X = A_X e^{i\phi_X} \\ U_Y = A_Y e^{i\phi_Y} \end{array}\right\} \rightarrow \text{Telescope \& Instrument} \rightarrow \left\{\begin{array}{l} A_{XX} e^{i\phi_{XX}} \\ A_{XY} e^{i\phi_{XY}} \\ A_{YY} e^{i\phi_{YY}} \\ A_{YX} e^{i\phi_{YX}} \end{array}\right.$$

Focal plane

Rearrange these to give:

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

Vector wave image formation

$$\vec{U}_3(x_3, y_3) =$$

$$\mathrm{K}\left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[\vec{U}_2^{\,-}(\xi_2,\eta_2)]\bullet\underline{\vec{\tau}_2(\xi_2,\eta_2)}\exp\left\{-j\frac{2\pi}{\lambda f}(x_3,\xi_2+y_3,\eta_2)\right\}d\xi_2\,d\eta_2\right]$$

In astronomical telescopes and instruments the term $\vec{\tau}_2(\xi_2,\eta_2)$ is a **vector** and $\vec{U}_3(x_3,y_3)$ depends on **BOTH** the polarization properties of the **source** & **the telescope/instrument.**

Pupil transmittance complex Jones vector

$$\vec{\tau}_2(\xi_2,\eta_2) = \begin{vmatrix} J_{XX} & J_{XY} \\ J_{YX} & J_{YY} \end{vmatrix}$$

Where J_{XX} is $\vec{\mathrm{X}}$ light *in* $\vec{\mathrm{X}}$ light *out* and J_{XY} is the $\vec{\mathrm{X}}$ light *in* that has been projected into $\vec{\mathrm{Y}}$

Comment

- How bad is it?
- Calculate how much light reflecting from a metal surface is polarized?
- Fresnel and later Maxwell
- Recent: Metallurgical Ellipsometry has made this an industry
  - Used to determine alloys in metals processing
  - "How much Mn do we put in that steel to harden it"?

Fresnel (1823) equations & definitions

$$N_0 = 1.$$

For metals, index is complex: $N_1 = n_1 - ik_1$

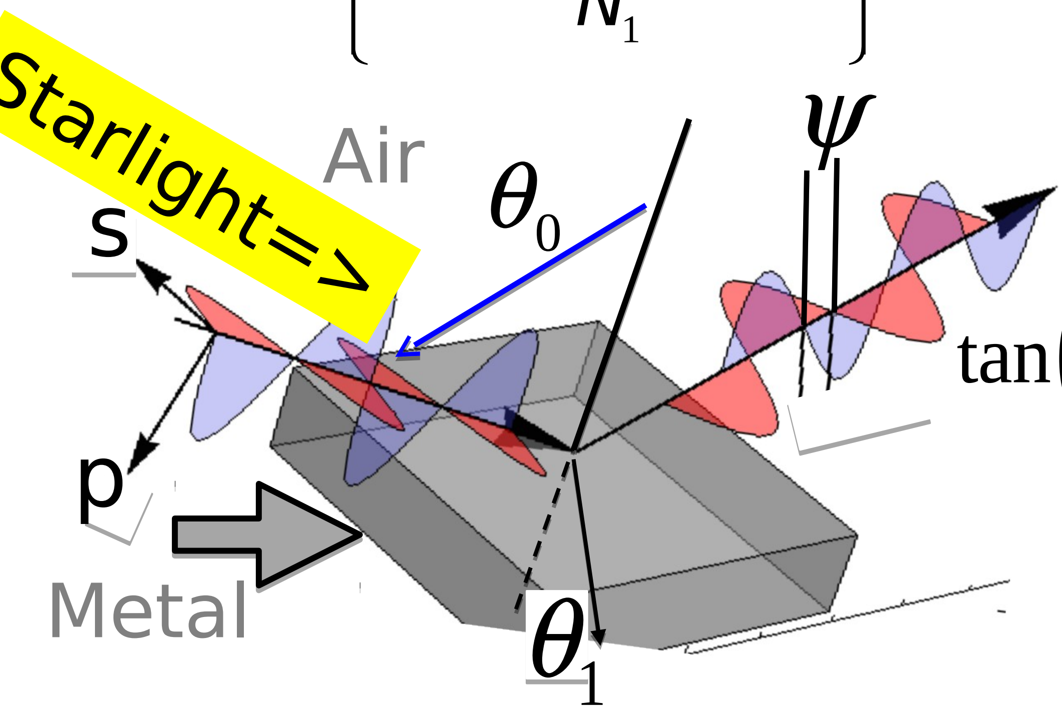
$$\theta_1 = \arccos\left\{ \frac{\sqrt{N_1^2 - N_0^2 \sin^2\theta_0}}{N_1} \right\}$$

$$r_p = \frac{\tan(\theta_0 - \theta_1)}{\tan(\theta_0 + \theta_1)}$$

$$r_s = \frac{-\sin(\theta_0 - \theta_1)}{\sin(\theta_0 + \theta_1)}$$

$$\left. \begin{matrix} \theta_1 \\ r_p \\ r_s \end{matrix} \right\} Complex$$

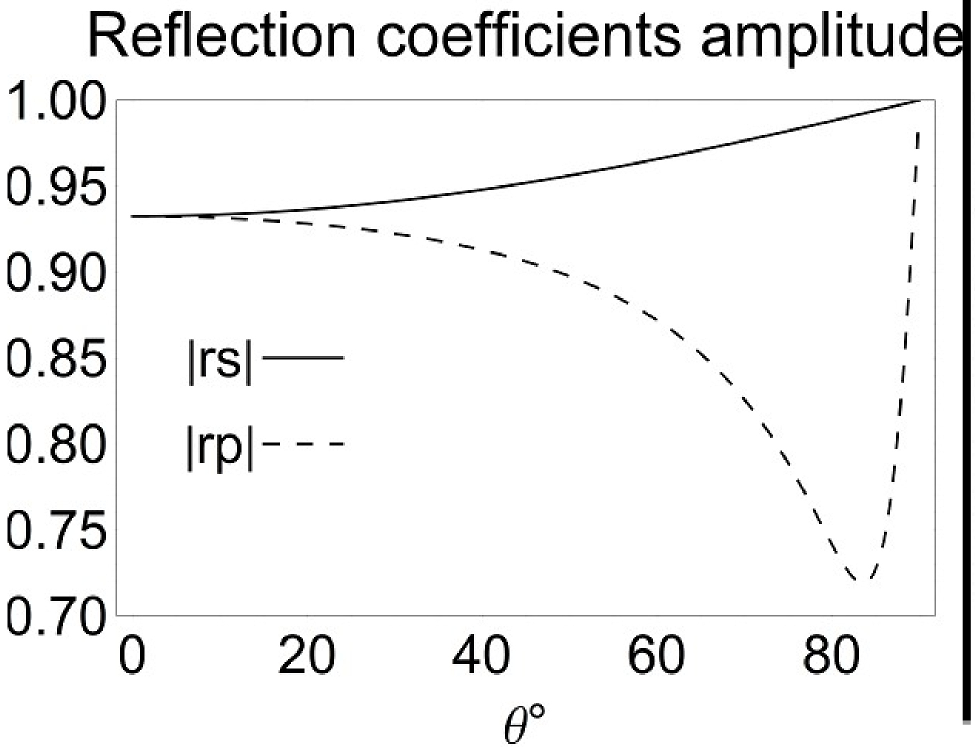
$$\frac{r_s - r_p}{r_s + r_p} = \text{diattenuation}$$

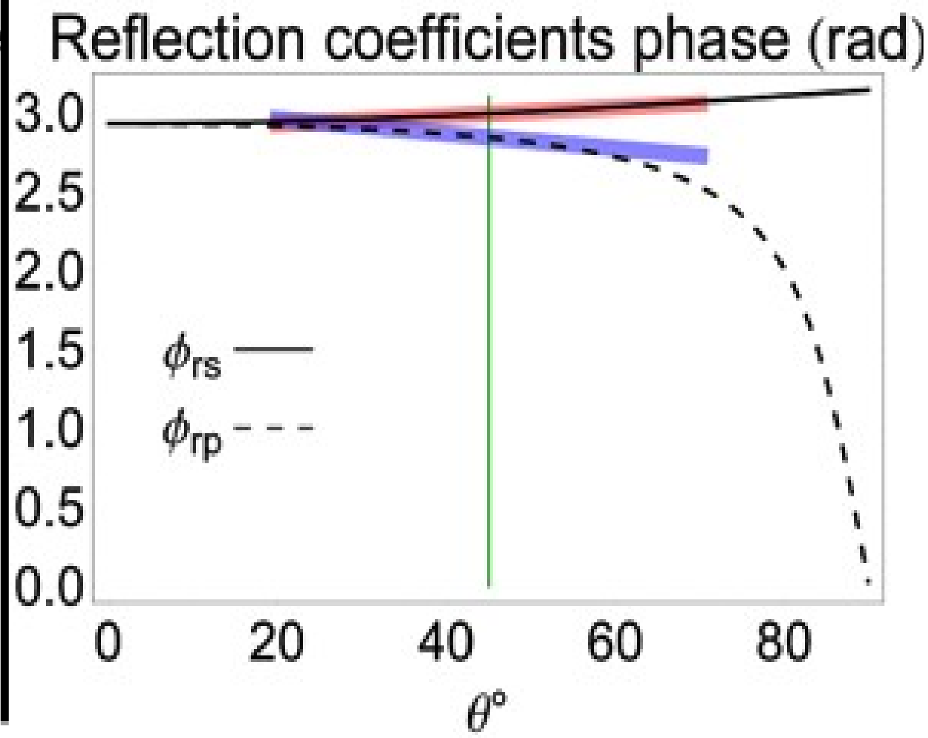


$$\tan(\psi) = \tan(\phi_S - \phi_P) = |r_p| / |r_s|$$

ψ is called retardance

Reflection coefficients (A & ϕ) for Al @ 800 nm; N_1 = 2.80 + 8.45i

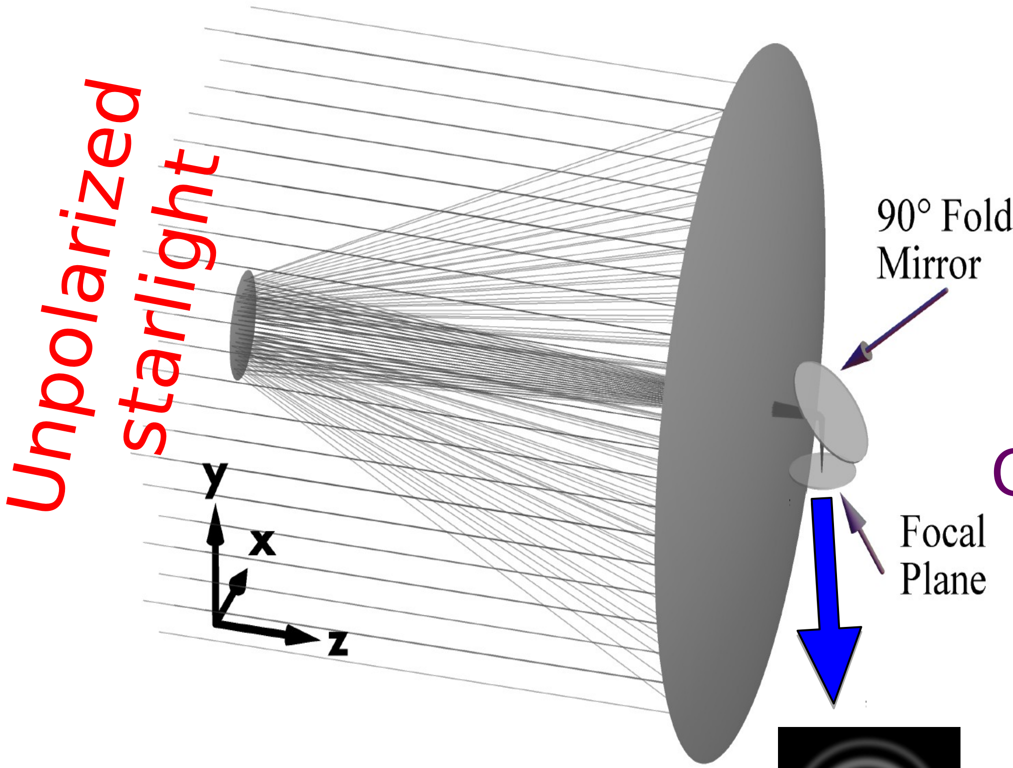




The two polarization aberrations are

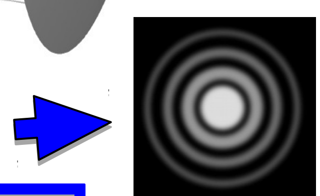
$$\frac{r_s - r_p}{r_s + r_p} = \text{diattenuation and retardance } \left(\tan\psi = \left|r_p\right| / \left|r_s\right| \right)$$

Polarization ray trace a 3-element minimally complicated (no A/R coat, one fold) layout



2.4 meter F#=1.2 aluminum coated mirrors & F#=8 focus

Curvatures on the primary and secondary optimized for $W(x,y) = 0$.

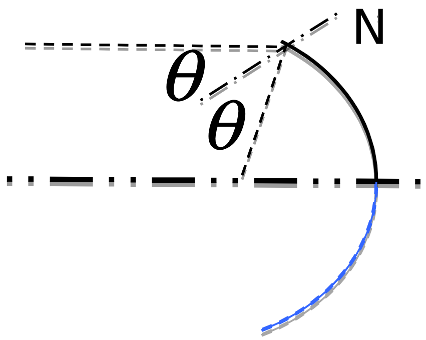


To design an optimum mask for exoplanets => model the focal plane electric field accurately.

We will find that $I(x, y)$ is the sum of 4 complex PSF's

Angles from curved surfaces

- The angle of incidence changes as the ray parallel to the axis “marches” across the curved mirror.
- For an unobscured coronagraph the angles are ~2x steeper because the mirror is off axis.

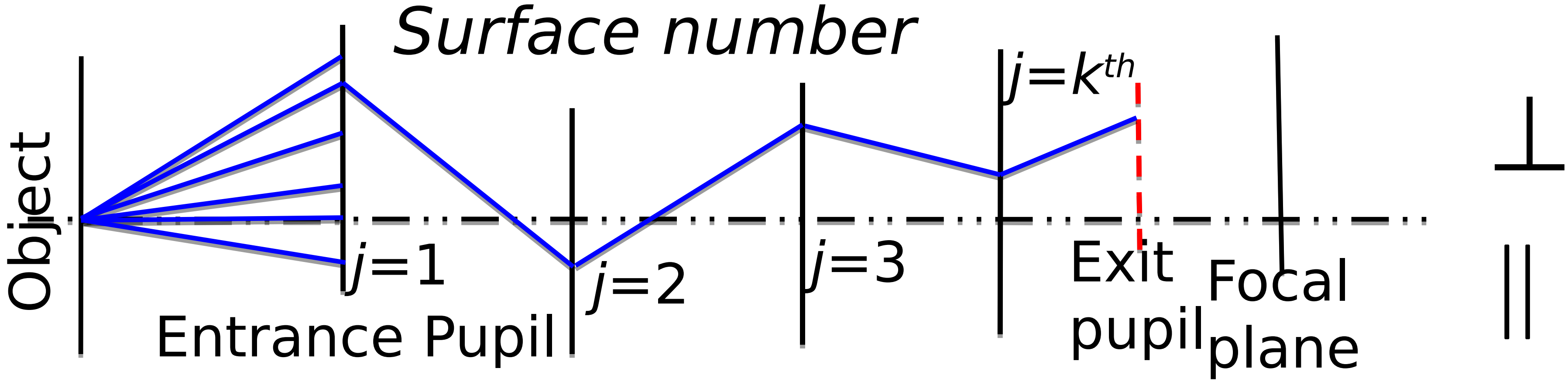


$$\theta = \frac{1}{2}\arctan\left[\frac{1}{2(f\#)}\right]$$

F#	Marginal ray angle of incidence in degrees
0.8	16.0
1.	13.3
1.2	11.3
1.6	8.7

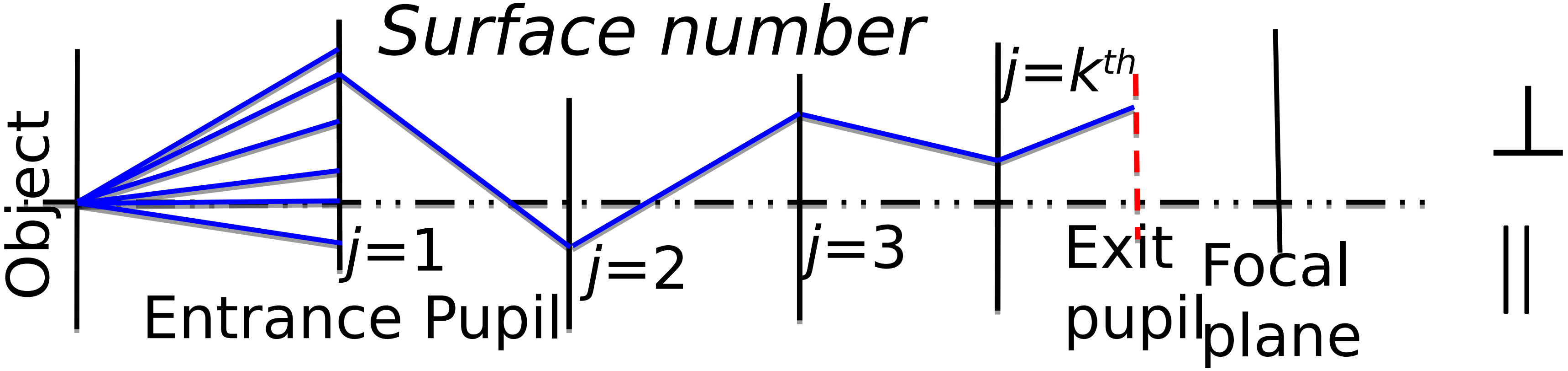
Therefore the pupil is polarization apodized and will change the detailed shape of the PSF

How to calculate the PSF for each polarization



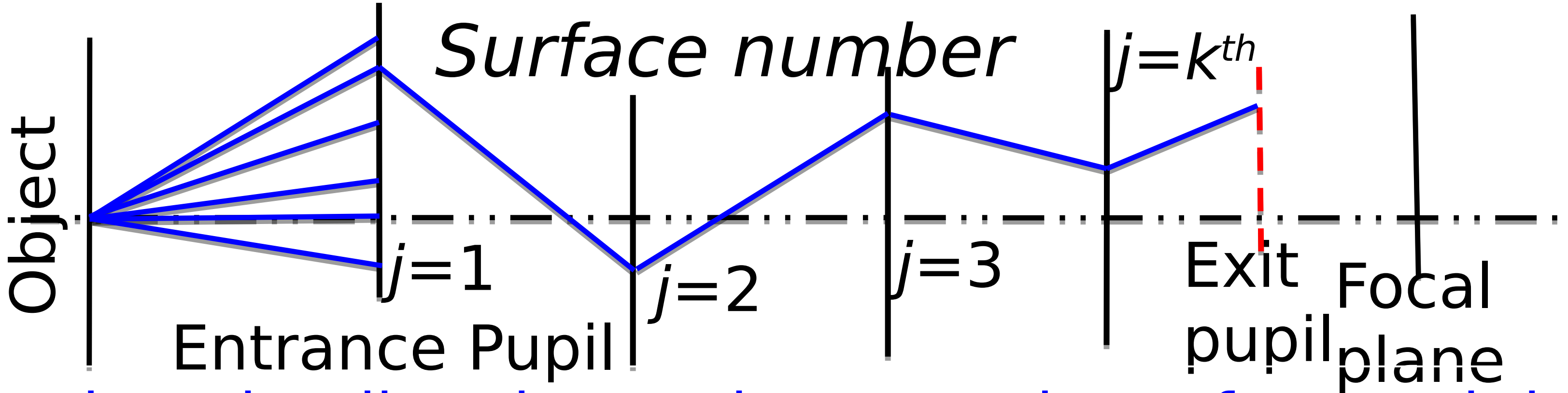
- **The Fresnel equations give us a different set of amplitudes and phases for the parallel polarized light ray bundle than they do for the perpendicular polarized light ray bundle**
- Therefore they are computed separately.
- Each object space point, which is represented by 2 rays is mapped to the **exit pupil** as 4 points, each carrying a complex number.

How to calculate the PSF for each polarization



- Packaging optical systems in small volumes to fit inside instrument compartments for current space telescopes requires compound angles in the optical path.
- The angle of incidence used in the Fresnel equations requires knowledge of the direction cosine of each reflecting surface in 3-dimensional space.

How to calculate the PSF for each polarization

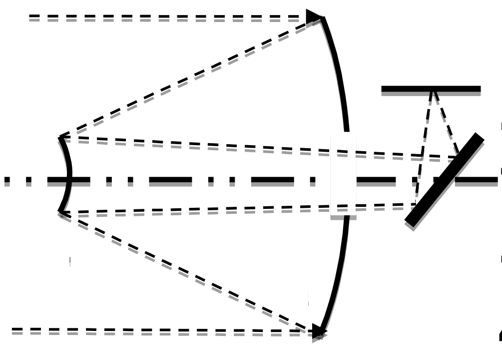


Based on the direction cosine at each surface and the physical properties of each surface $(n-ik)$ we use the Fresnel equations to calculate the **amplitude change** and the **phase change** for each ray at each surface

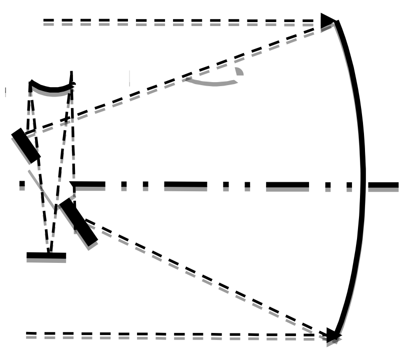
Compute the multiplicative amplitude and cumulative phase for both the $\parallel$ and the $\perp$ light for each ray traced across the entrance pupil & map these 4 complex arrays onto the exit pupil.

Sequence of the calculations

The transfer function $\vec{g}$ depends on the order (or sequence) in which light passes through the system



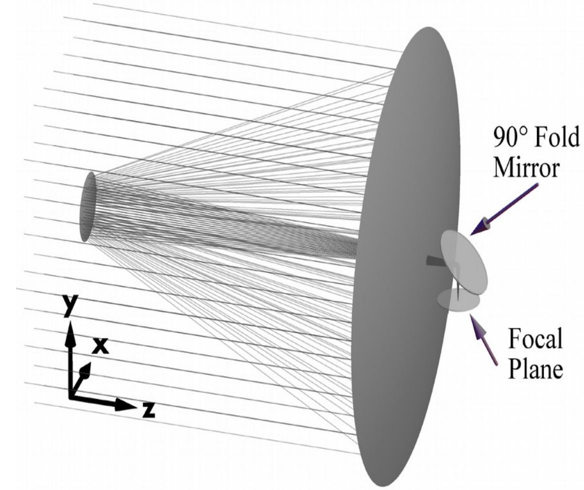
1. Concave
2. Convex
3. Fold flat
4. Focal plane



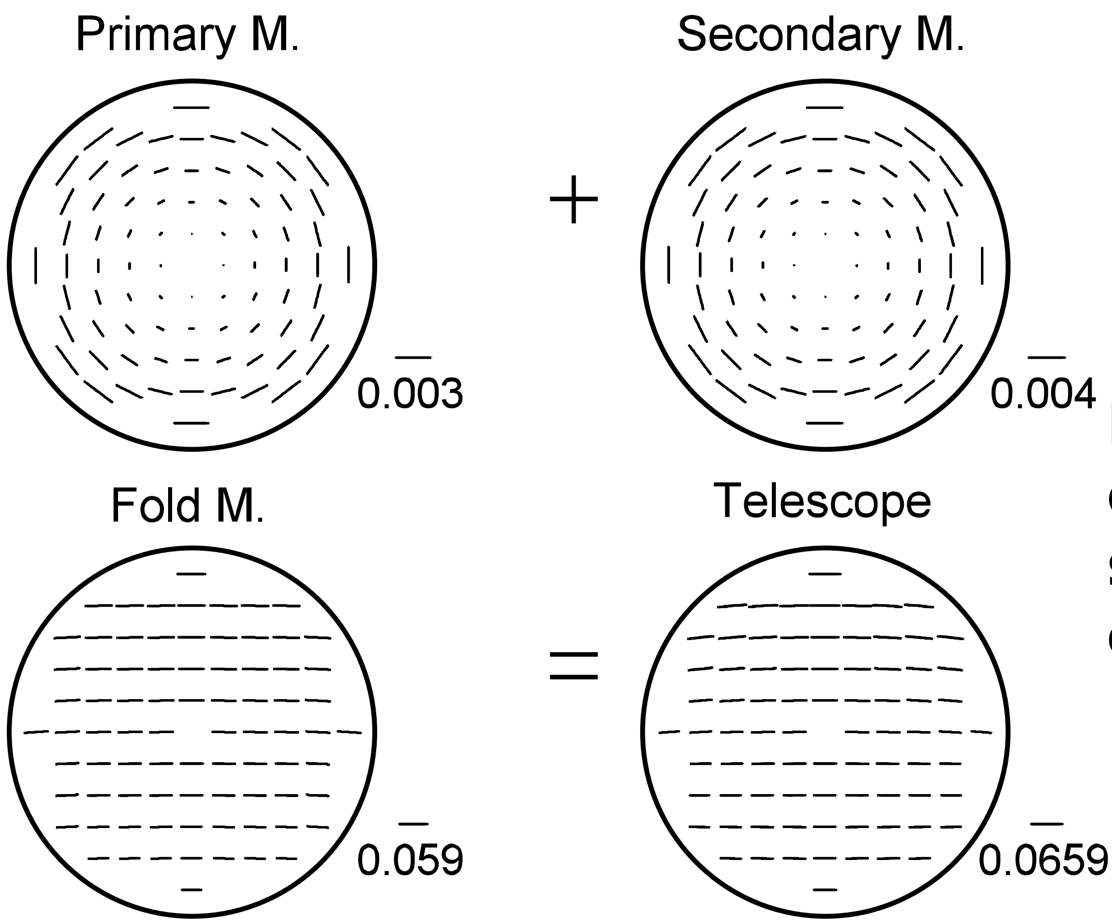
1. Concave
2. Fold flat
3. Convex
4. Focal plane

The transfer function is different for each of these opto-mechanical configurations

$$\frac{r_s(\xi,\eta) - r_p(\xi,\eta)}{r_s(\xi,\eta) + r_p(\xi,\eta)} = D$$



diattenuation face-on surface maps



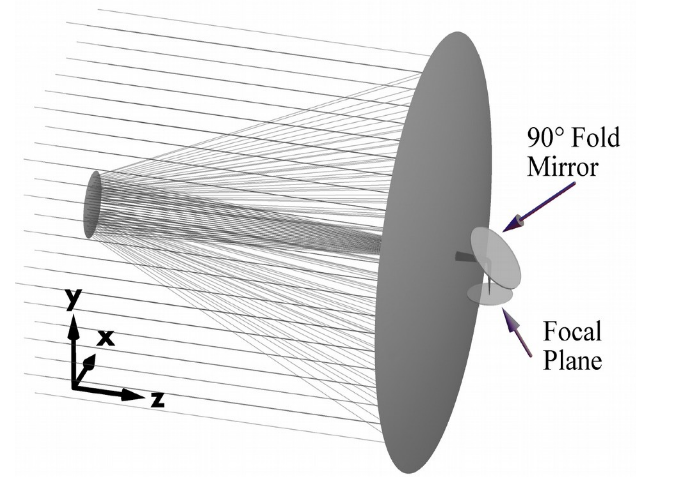
Primary is F/# =1.2 and the F/# at the focal plane is 8.

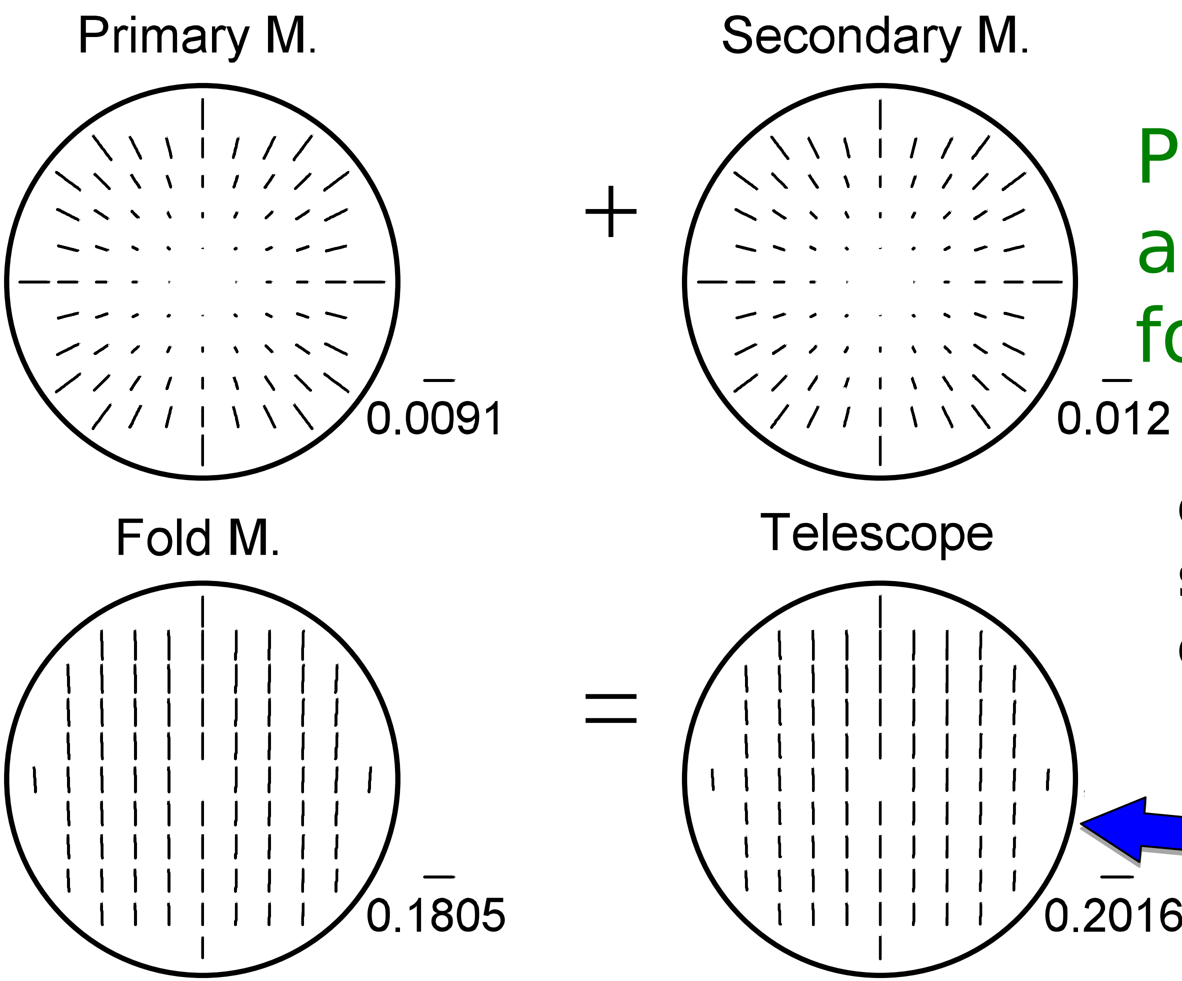
Length of the line & orientation shows the vector of the diattenuation

Exit pupil

$$\tan\left(\psi(\xi,\eta)\right) = \tan\left(\phi_S(\xi,\eta) - \phi_P(\xi,\eta)\right)$$

retardance face-on surface maps





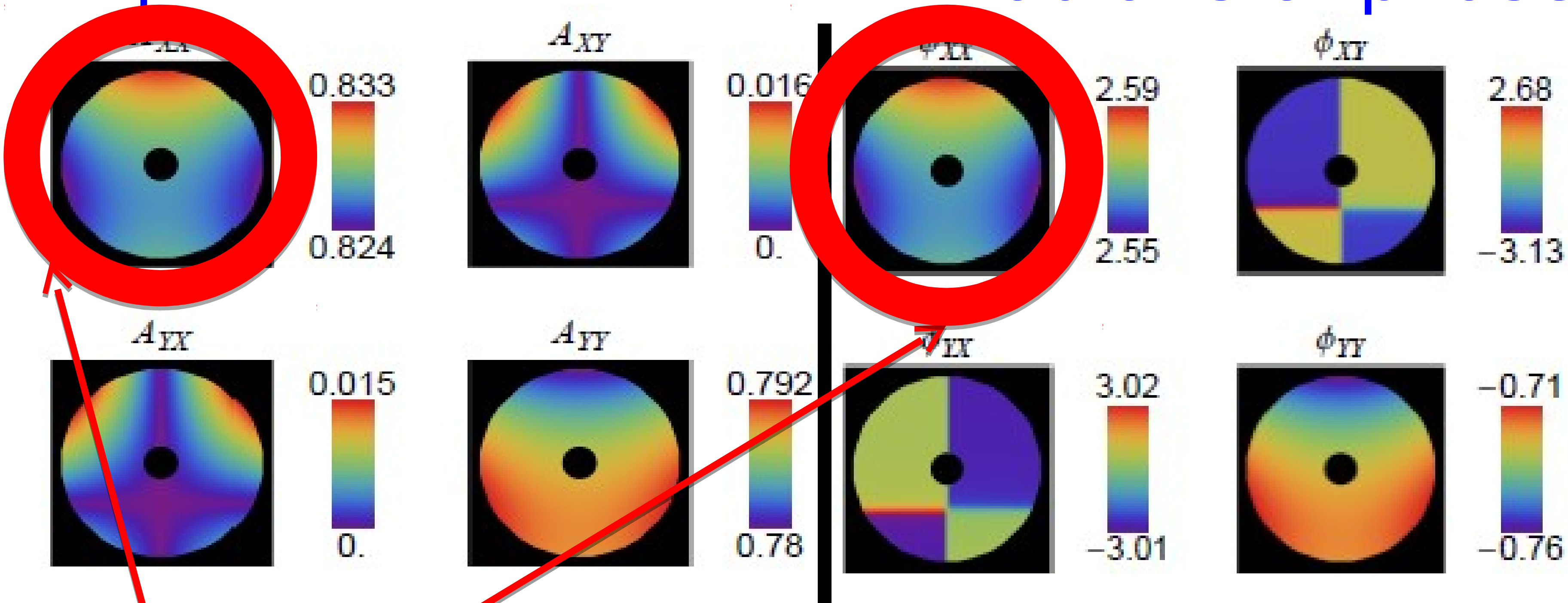
Primary is F/# =1.2 and the F/# at the focal plane is 8.

Length of the line & orientation shows the vector of the retardance

Exit pupil

Map & group the functions

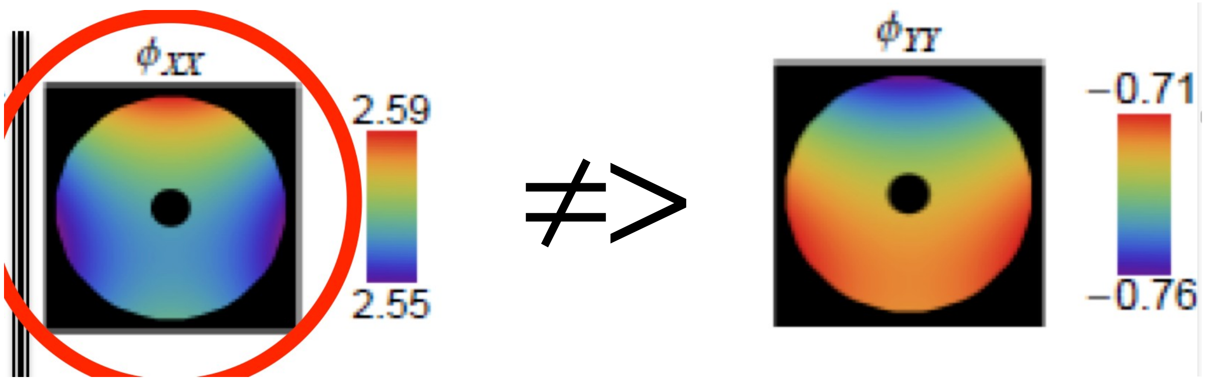
Amplitude normalized   Radians of phase



Jones vector

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

Polarization dependent wedge



- The orthogonally polarized components contain different wavefront aberrations, which differ by approximately 32 milliwaves.
- A single A/O system cannot correct for both polarizations simultaneously
- Wedge between the two gives .6 milli arc seconds shear

The perpendicular ray Y is 9% brighter than the parallel ray for this system

How do we calculate the vector PSF?

- The **electric field** at the focal plane is given by

$$U_3(x_3, y_3) =$$

$$\mathrm{K}\left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\begin{bmatrix} J_{XX} & J_{XY} \\ J_{YX} & J_{YY} \end{bmatrix}\exp\left\{-j\frac{2\pi}{\lambda f}\left(x_3,\xi_2 + y_3,\eta_2\right)\right\}d\xi_2\, d\eta_2\right]$$

And the focal plane intensities are given by

$$I_3(x_3, y_3) = \left|U_3(x_3, y_3)\right|^2 =$$

$$\left|\mathcal{F}(J_{XX})\right|^2 + \left|\mathcal{F}(J_{YY})\right|^2 + \left|\mathcal{F}(J_{YX})\right|^2 + \left|\mathcal{F}(J_{XY})\right|^2$$

The telescope PSF is the linear (uncorrelated) superposition of these 4 PSF’s

How do we calculate the vector PSF?

The complex field at the focal plane is given by

$$U_3(x_3, y_3) = \mathcal{F}\{J_{XX} + J_{YY} + J_{XY} + J_{YX}\}$$

The intensity is then

$$I_3(x_3, y_3) = |U_3(x_3, y_3)|^2 = |\mathcal{F}\{J_{XX} + J_{YY} + J_{XY} + J_{YX}\}|^2$$

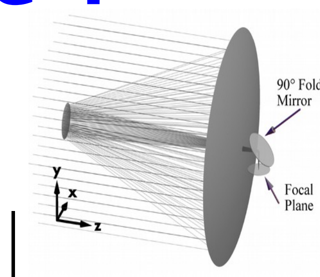
E. Wolf [Theory Of Coherence & Polarization Of Light (Cambridge2007)] shows that these four fields are not correlated and are therefore incoherent.

The intensity at the focal plane is then the incoherent sum:

$$I_3(x_3, y_3) = |\mathcal{F}(J_{XX})|^2 + |\mathcal{F}(J_{YY})|^2 + |\mathcal{F}(J_{YX})|^2 + |\mathcal{F}(J_{XY})|^2$$

The telescope PSF is the linear (uncorrelated) superposition of these 4 separate PSF's

Propagate the exit pupil field to map the 4 independent PSF's to the image plane



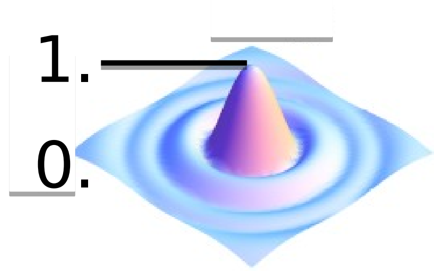
Amplitude Response Matrix

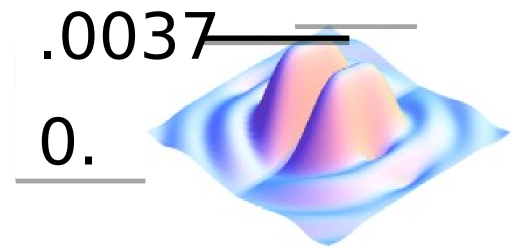
$$= \mathbf{ARM} = \begin{vmatrix} \Im\left[J_{XX}(x,y)\right] & \Im\left[J_{XY}(x,y)\right] \\ \Im\left[J_{YX}(x,y)\right] & \Im\left[J_{YY}(x,y)\right] \end{vmatrix}$$

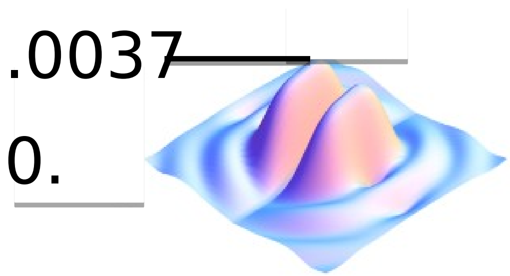
What does the focal plane look like?

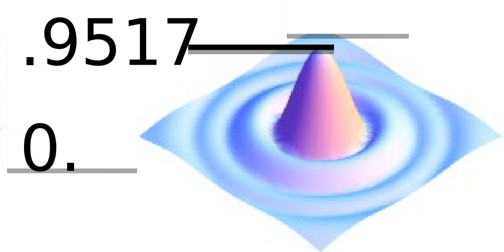
$$\left|\Im\left[J_{XX}(x,y)\right]\right|^2 \quad \left|\Im\left[J_{XY}(x,y)\right]\right|^2$$

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

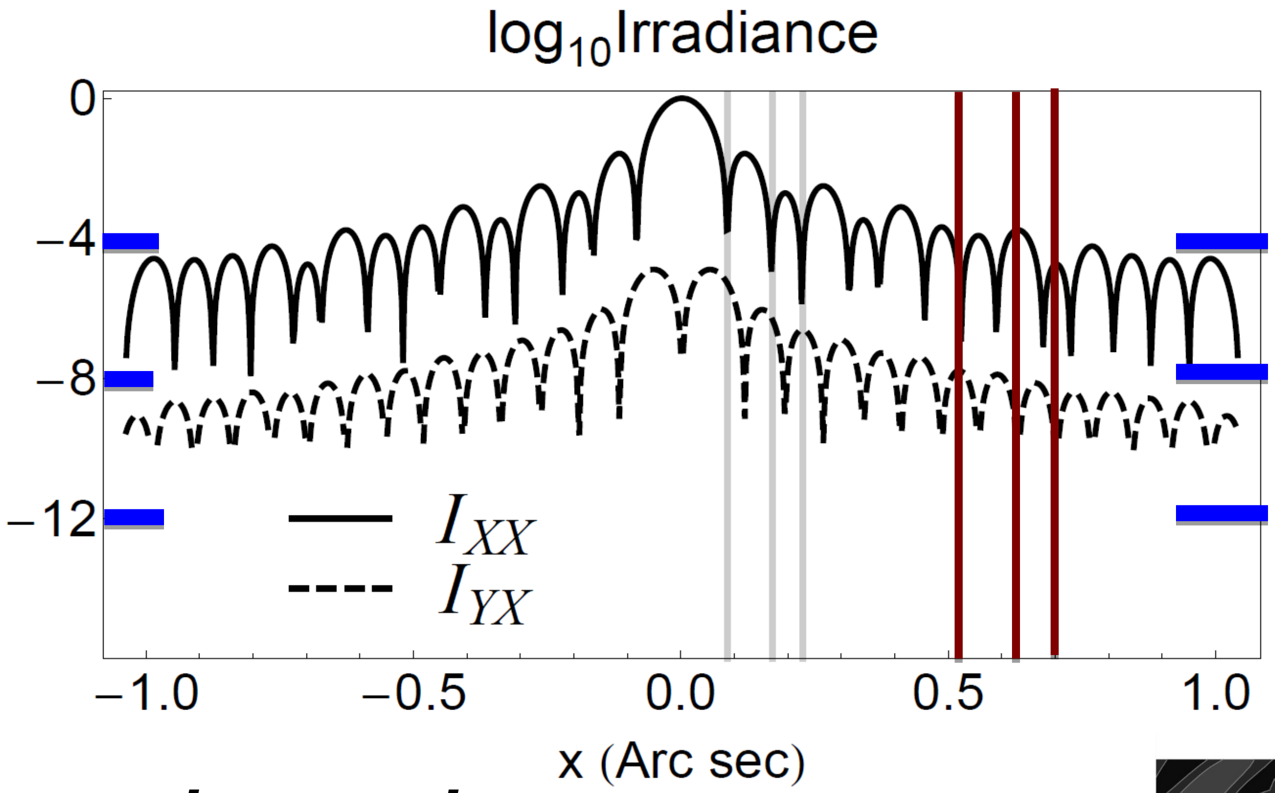


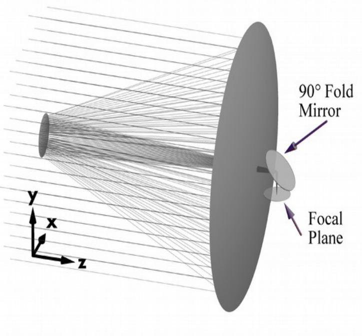






Polarization PSF (I_{XX}) & the "ghost" PSF (I_{YX}) for the 2.4 meter telescope - note the **"zeros" do not line up**

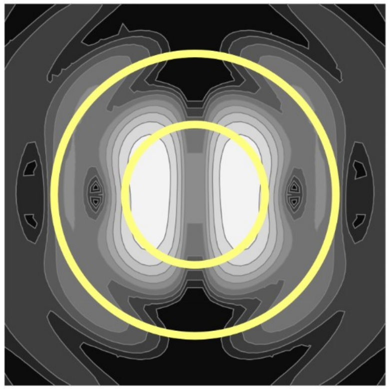




I_{XX} I_{XY}

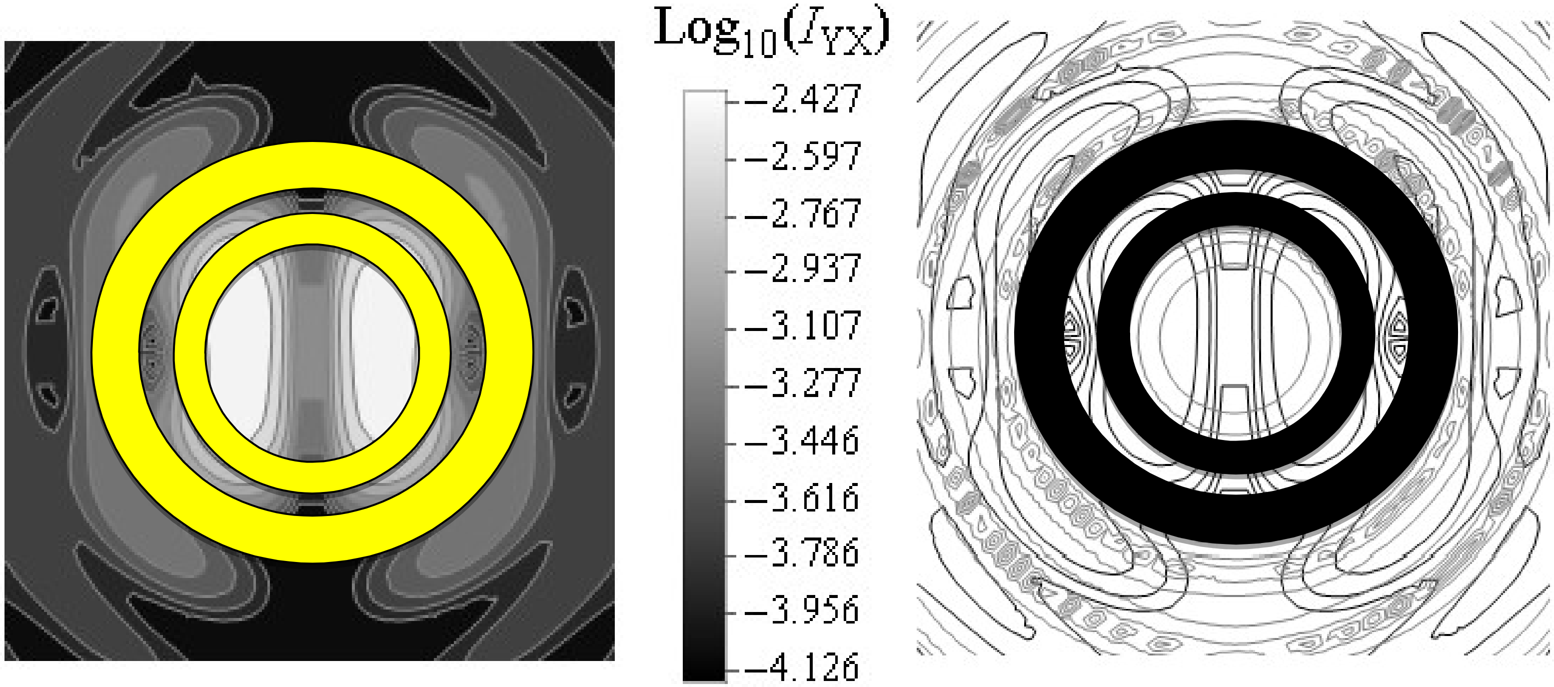
I_{YX} I_{YY}

Face-on ghost PSF

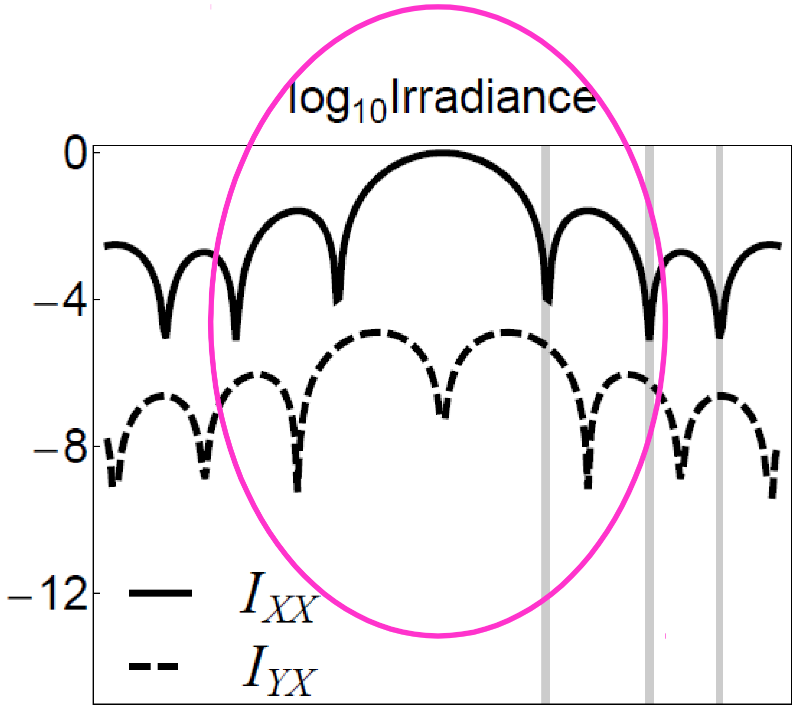


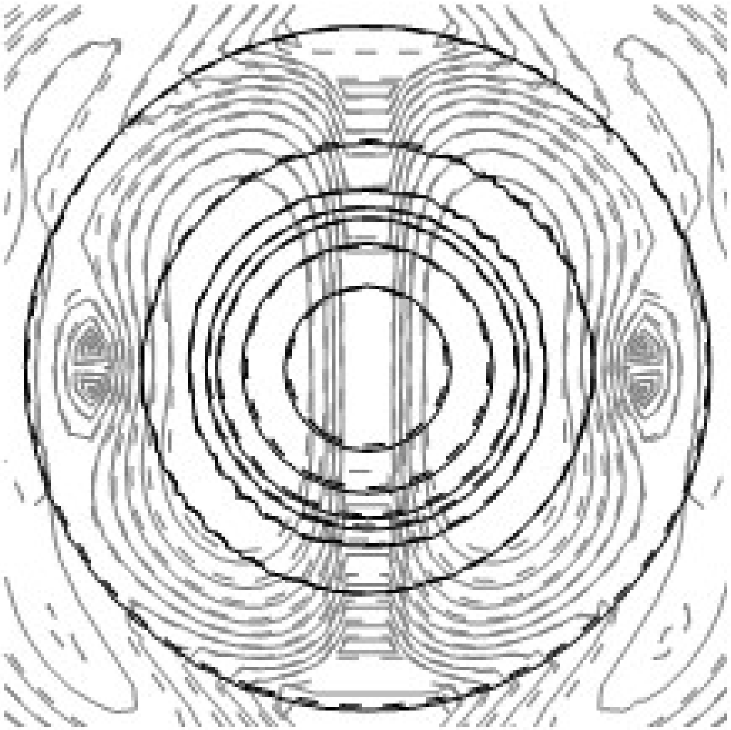
The ghost PSF is too faint to matter – not always!

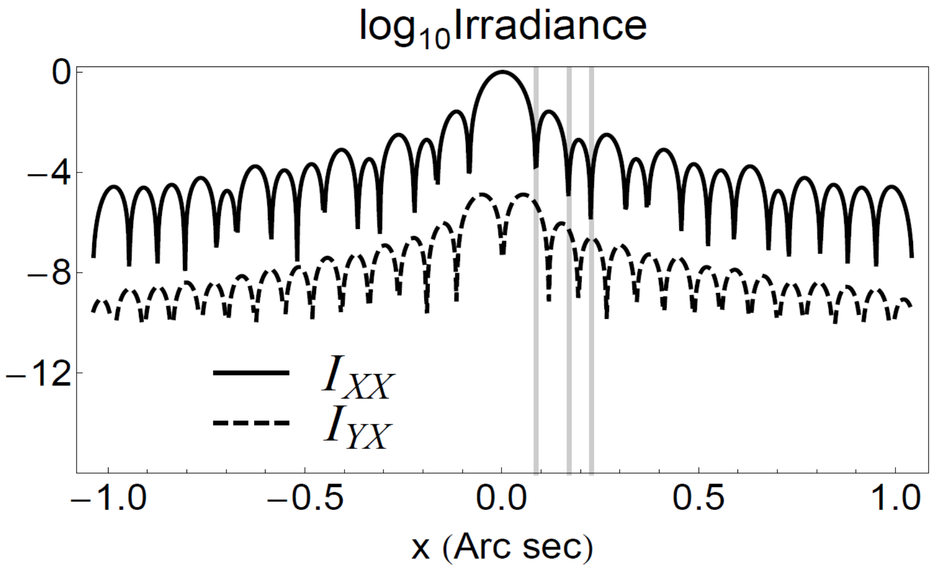
- The opto-mechanical system analyzed above is a simple Cassegrain followed by a single fold mirror in front of the detector.
- Breckinridge, Lam and Chipman (2015) show that the intensity of the ***ghost increases*** with the ***square*** of the ***number of fold mirrors*****.**
- **The WFIRST-CGI space coronagraph system, has 18 reflections before the mask to limit contrast to 10^{-5} not the required 10^{-7}.**

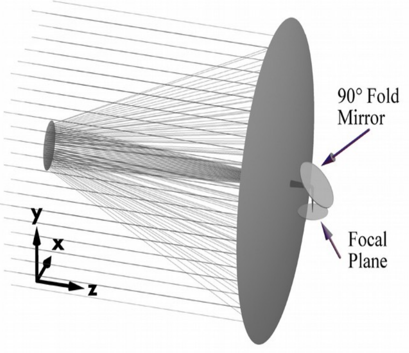

$Log_{10}(I_{YX})$
−2.427
−2.597
−2.767
−2.937
−3.107
−3.277
−3.446
−3.616
−3.786
−3.956
−4.126

Intensity slices and contour plots of PSF show magnitude of the cross-product ghost and the PSF polarization shear

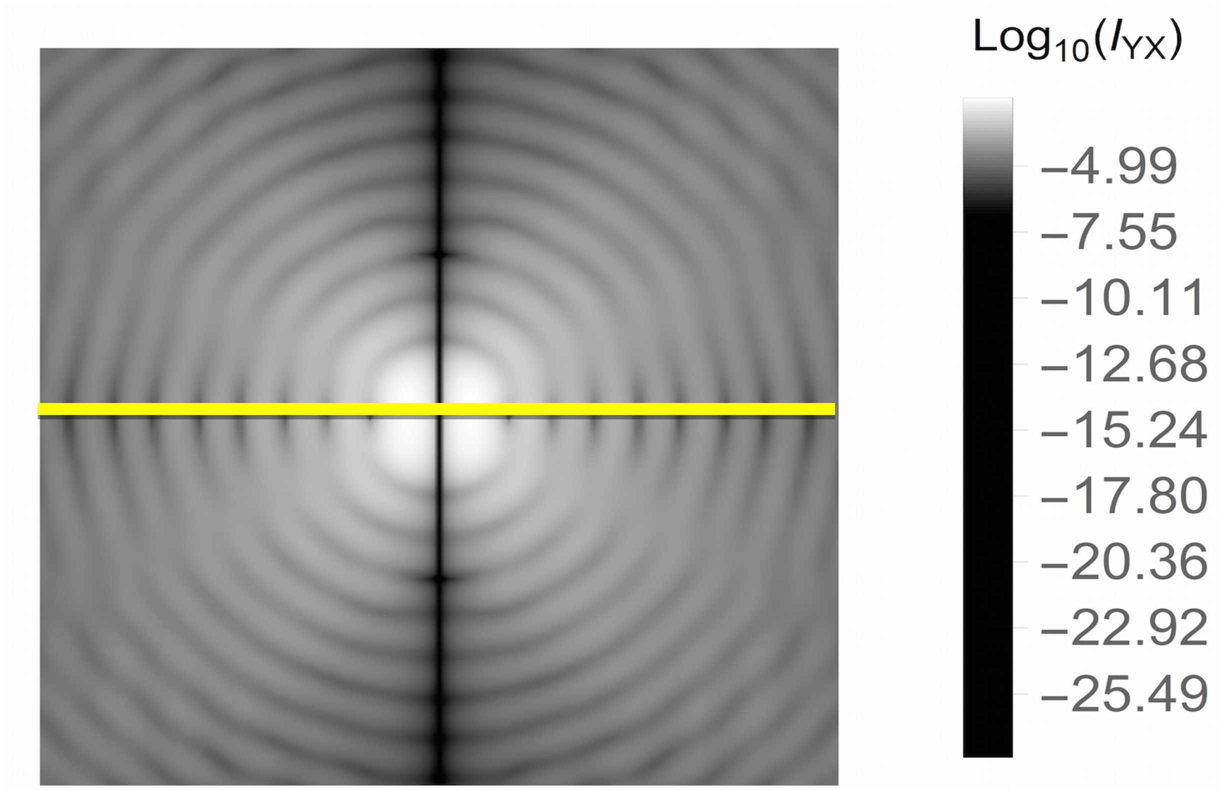


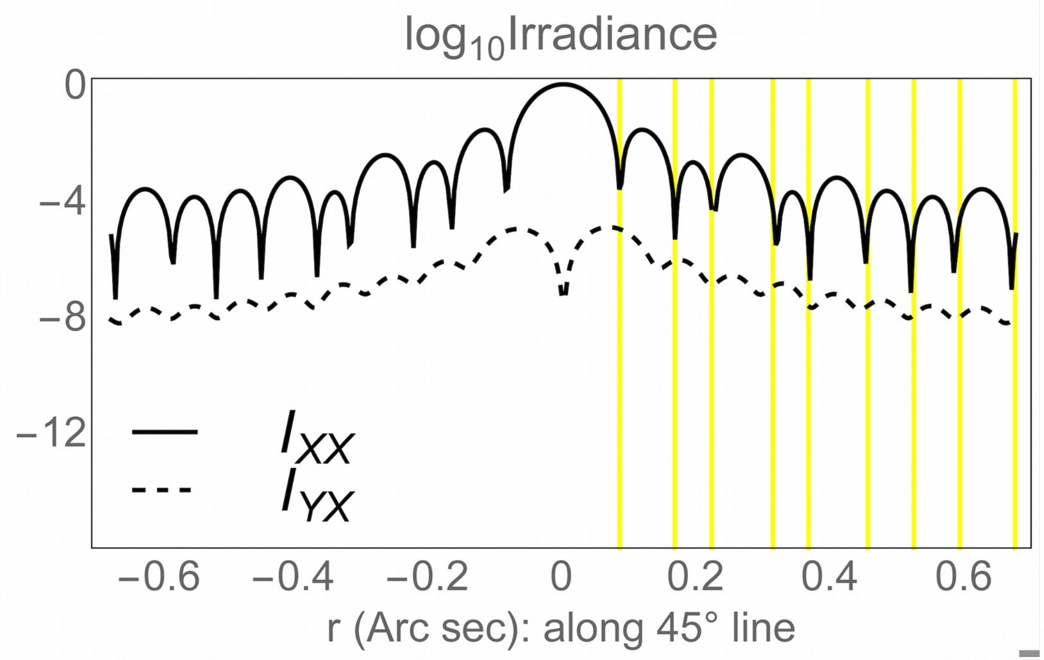


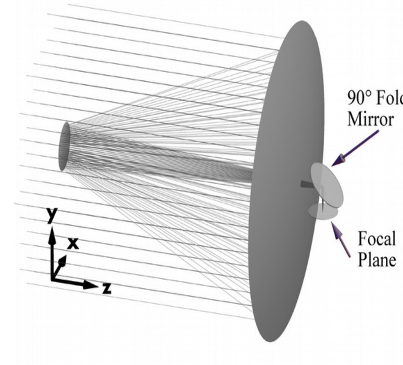




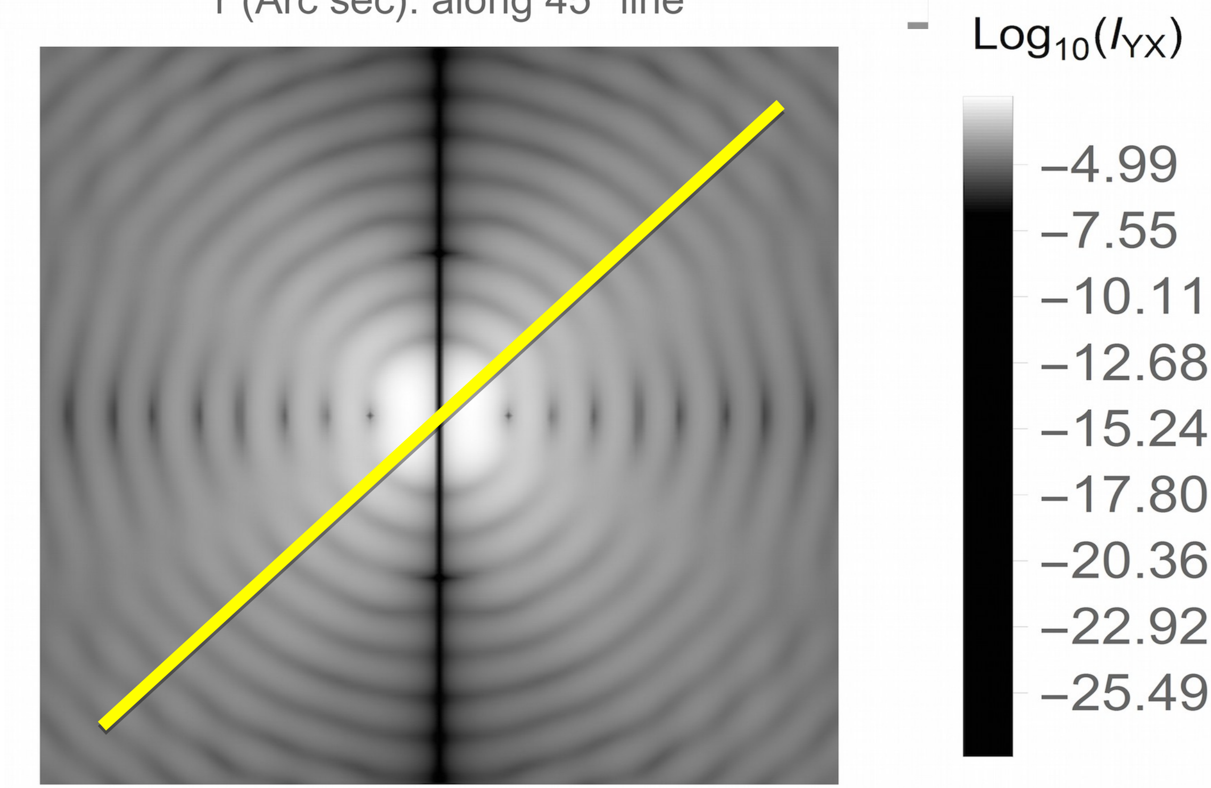
$\text{Log}_{10}\ I_{YX}$ at a 0 degree slice



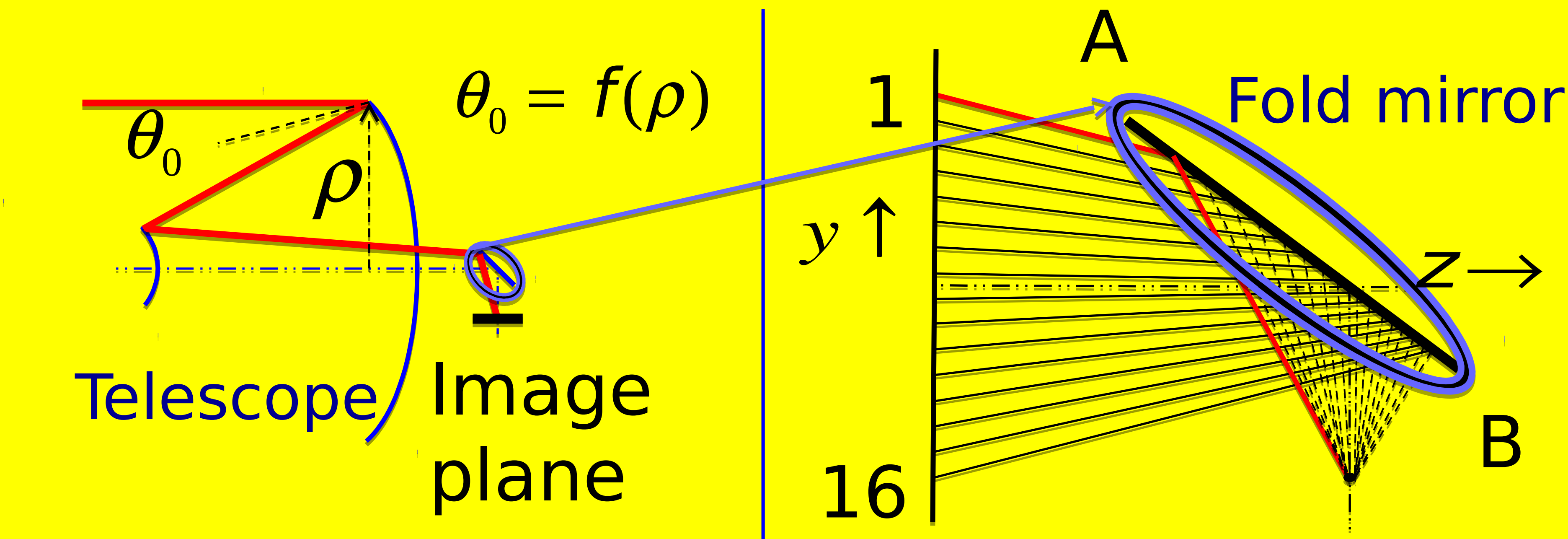




$\mathrm{Log}_{10}\ I_{YX}$ at a 45 degree slice



Polarization depends on incidence angle



The incident rays march across the pupil strike the mirror at different angles, depending on radius

Incident rays march across the fold mirror striking at decreasing angles from the top down

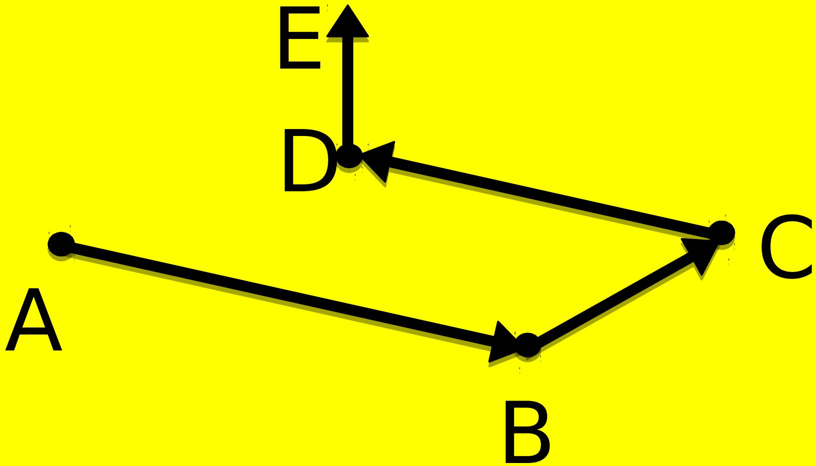
Comment

- If we identify sources & the magnitude of their contribution of unwanted polarization in high-fidelity optical systems
- **We can begin to develop mitigation strategies**

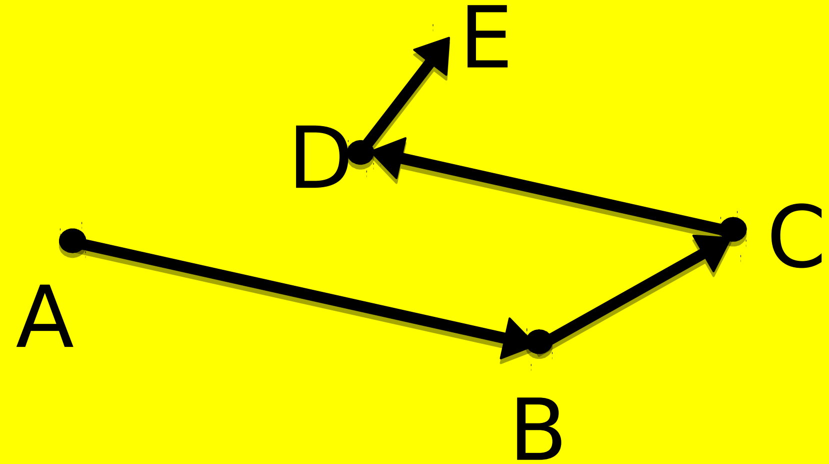
Sources

- Opto-mechanical packaging
  - Unnecessary fold mirrors
  - High angle of incidence rays
  - Low F# powered optical elements
  - Compound angles
- Coatings
  - Deposition of highly reflecting metals and dielectric overcoats that have anisotropic complex reflectivity properties
- Dispersive optical elements
  - Diffraction gratings
- Stops and masks
  - Poor design and manufacture
- Transmission elements
  - Stress birefringence
  - Tilted surfaces
- Adaptive optics system
  - Improperly tuned
- Design
  - Wide fields of view

Polarization cross talk is increased by a change of the Eigenstate of the of the propagating wavefront; tilted mirrors



All angles 90-degrees => then the Eigenstate of the final wavefront are mixed $\perp$ and $\|$

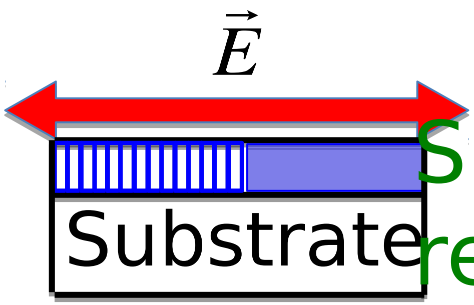


Mirror D now sends beam into a compound angle and the cross product terms increase

Polarization reflectivity anisotropy => changes polarization across wavefront surface
Flavio Horowitz, 1983 & Smith/Purcell 1953

- Anisotropy is produced by the coating processes used for large telescope mirrors

> $\vec{E}$ incident sees a different conductivity in the substrate depending on whether the wave is reflecting from an amporphous or the columnar structure



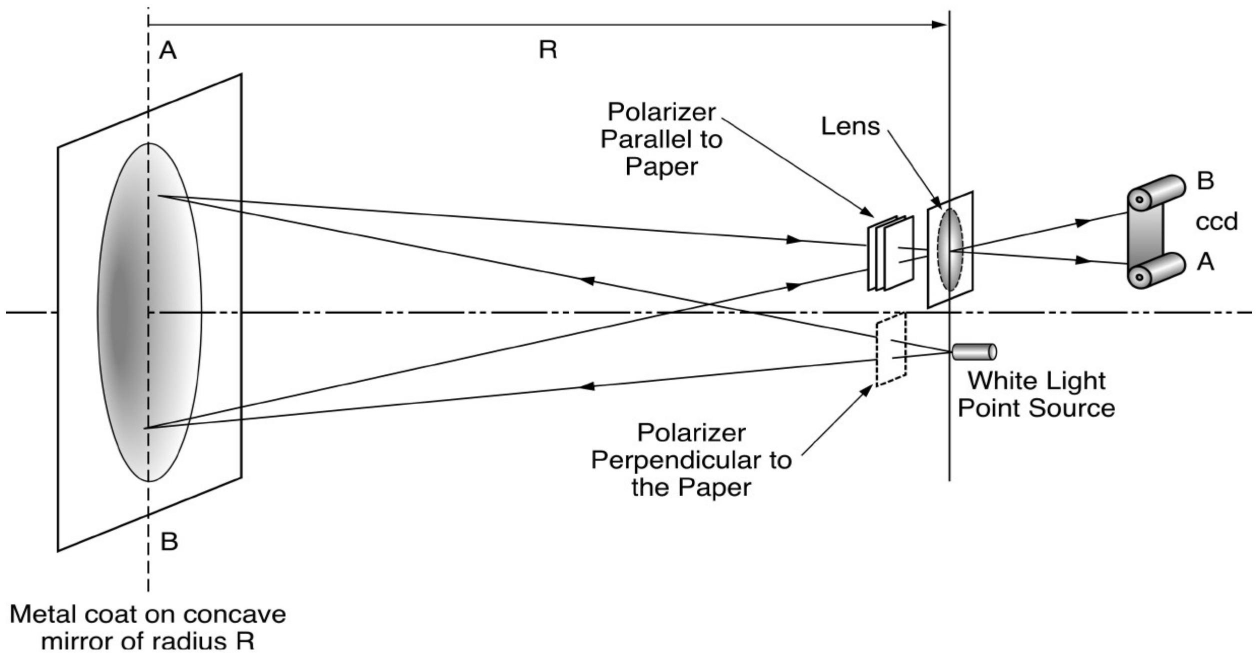
Side view of reflecting film

Left columnar (crystal)
Right amorphous micro-structure

$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Polarization reflectivity anisotropy

- Proposal to measure polarization cross-talk from a “typical” 4-meter class mirror.
- Once we can map the anisotropy in the complex reflectivity we can devise control methods



- **Does structure in the highly reflective coating make the 10pm tolerance impossible!**

Several ways to mitigate these effects One is to build a phase plate

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

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

$$\mathbf{J}_{\text{System}} = \left(\mathbf{J}_{\text{T+C}g\text{ph}}\right) \times \left(\mathbf{J}_{\text{Corrector}}\right) = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Mitigation in practice

- Change the tilt angles on mirrors by reconfiguring the opto-mechanical layout to optimize the configuration for minimum polarization
- Breckinridge, Lam & Chipman (2015) PASP tells us how to do that.
- Limited results in very complicated systems

gation: spatially variable retarder p

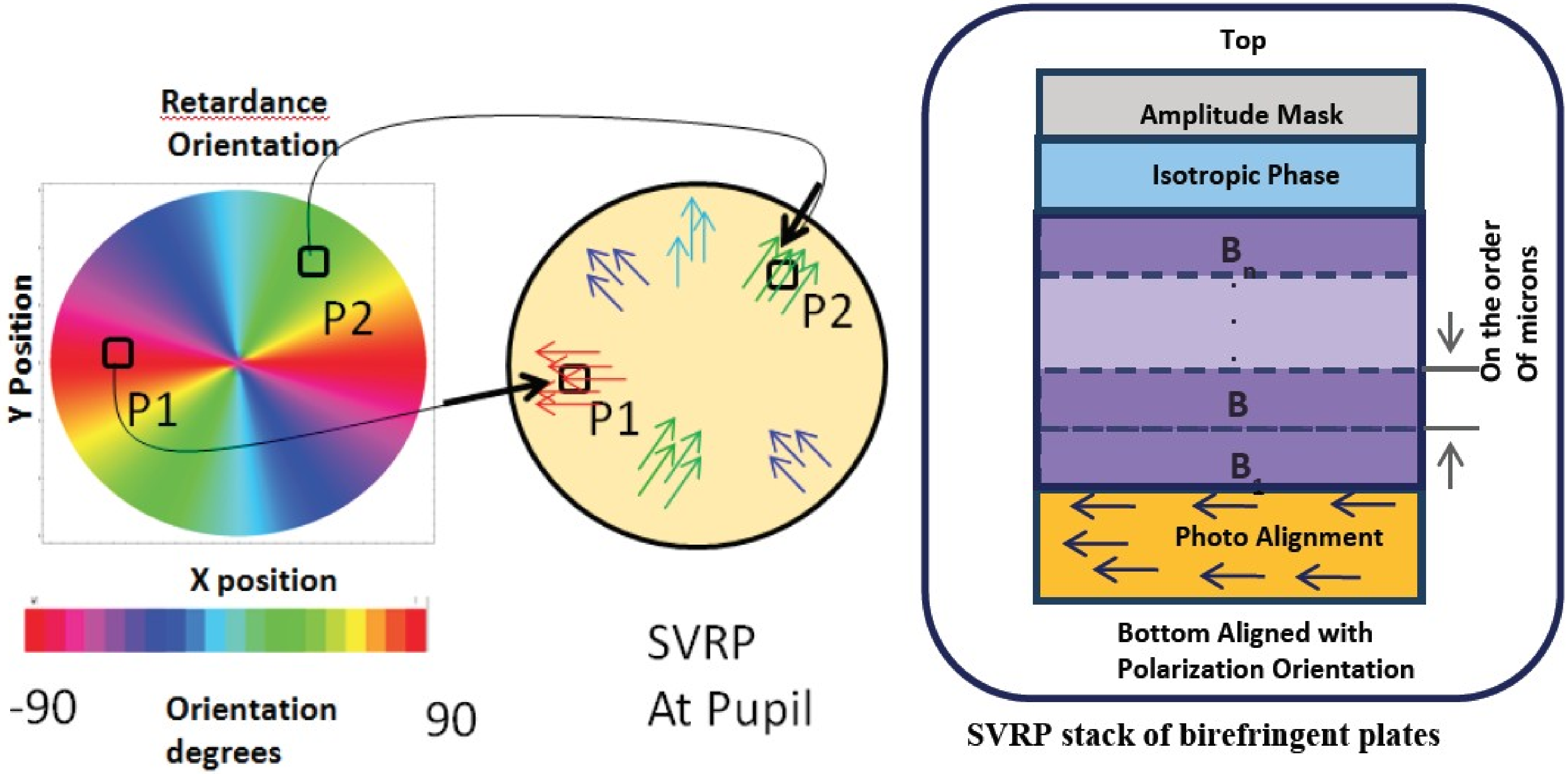
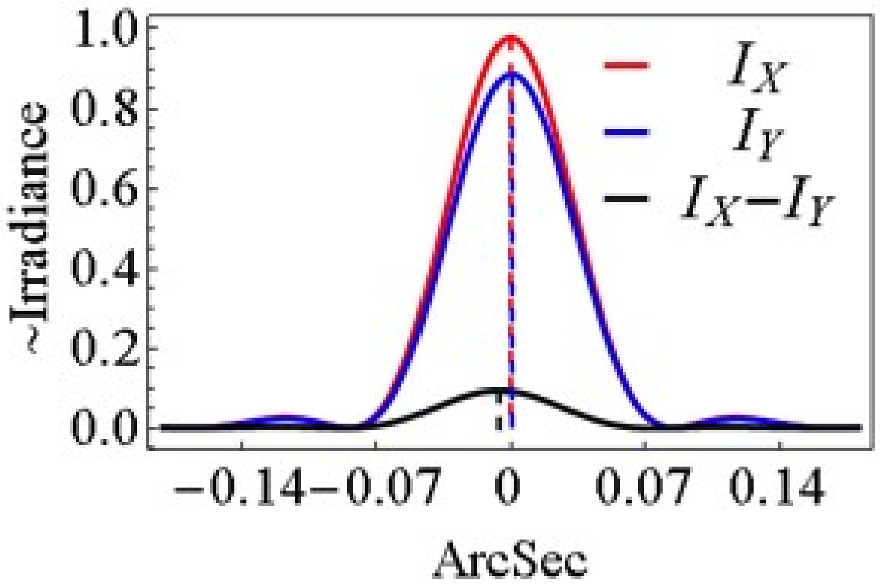
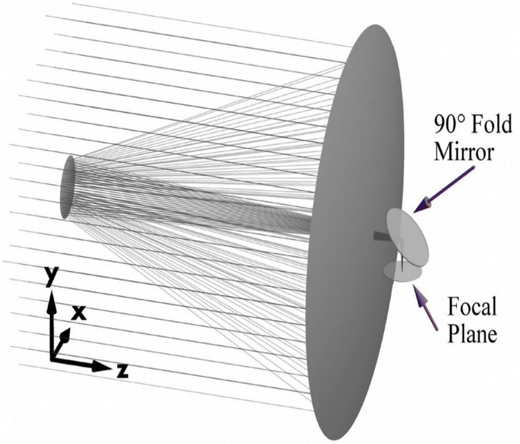


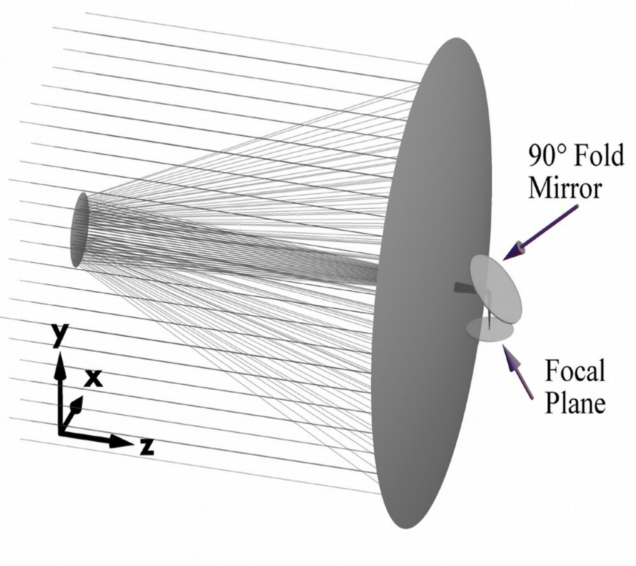
Figure 4. Photo alignment layer of a SVRP plate. (a) shows a spatially variable retarder plate (SVRP) face on (x,y) with retardance direction indicated by the colors shown in the stripe below which maps color into orientation in degrees as shown. (b) shows two particular regions, P1 and P2 which have 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.

PSF assymetry





The cross-section profiles of the I_X and I_Y PSF images, one for each polarization and the profile of their difference are shown in red and blue in arc seconds from the center of the PSF. The black line shows Stokes Q image, the difference between the two PSFs.



- PSF's flux,
- Radius of encircled energy,
- PSF shears – linear with # of mirrors
- PSF ellipticity for *X* and *Y*-polarized incident light.

For the Cassegrain + fold mirror

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

Linear polarizers do not mitigate these effects!

- A Wollaston beam splitter (WBS) prism placed over the focal plane does not unscramble the co-propagating mixed polarized signals.
  - They were mixed up-stream in the optical path
- Since the beams are deviated in a Wollaston, the Eigenstates are projected onto a rotated coordinate system & the power in the off-diagonal elements is increased.

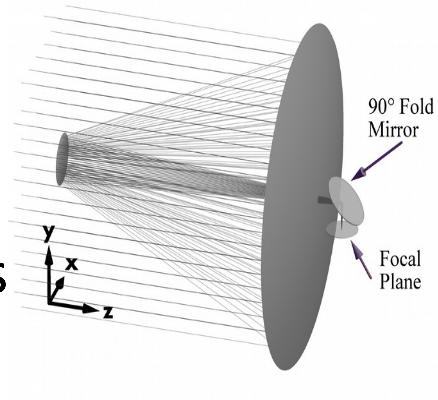
System polarization operator

- The 4x4 Mueller matrix is often used as the linear operator to describe how an optical system operates on an incoming beam of light

$$\begin{vmatrix} I \\ Q \\ U \\ V \end{vmatrix}_{IMAGE} = \begin{vmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{vmatrix}_{SYSTEM} \times \begin{vmatrix} I \\ Q \\ U \\ V \end{vmatrix}_{OBJECT}$$

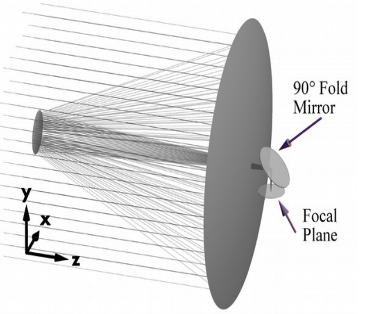
- The next charts show the 4x4 Mueller matrix for the Cassegrain telescope with fold mirror shown on page 24.

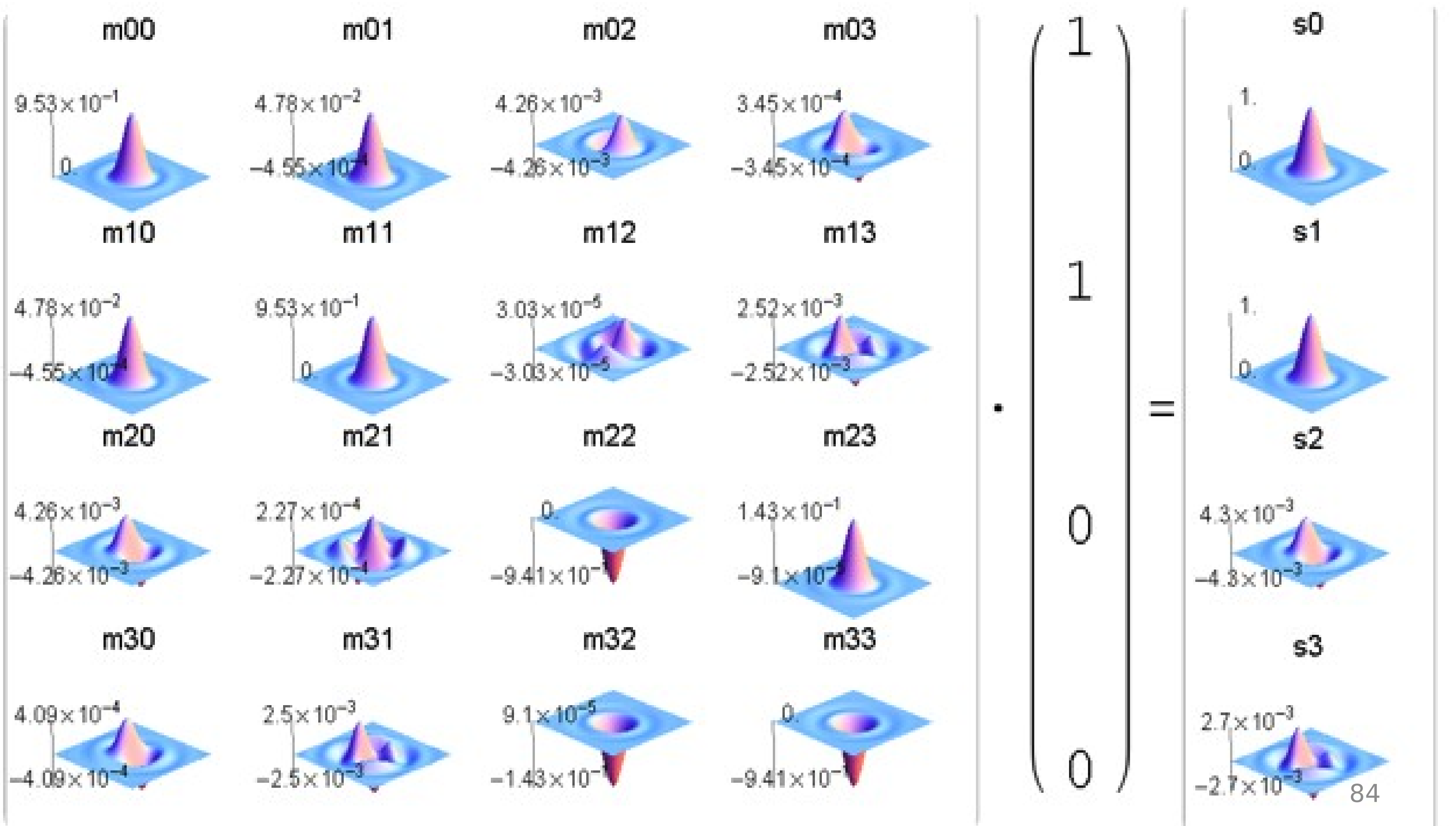
Comment



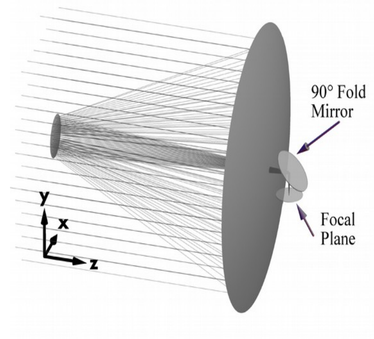
- The Mueller matrix is a 4x4 matrix of real numbers represent the properties of a telescope, device or instrument.
- A 1x4 column matrix represents the Stokes vector which describes the polarization content of a beam of light.
- When this beam of light strikes a surface or passes through a polarization filter the polarization state of the beam is changed.
- On the page after next we see the 4 x 4 Mueller matrix operator that represents the Cassegrain & fold mirror telescope we see in Chart 24.
- Each of the elements in the 4 x 4 matrix makes some contribution to the field. Some are insignificant.
- These contributions are plotted within each element to provide the reader with an intuitive understanding of how the aberrations evolve.

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



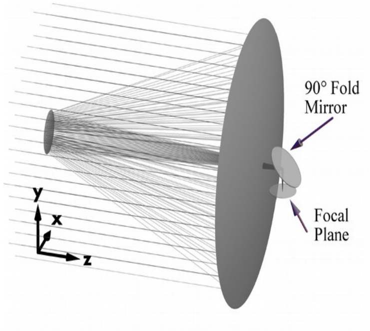


Summary for this telescope



- 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* is 0.625 masec
- *X* and *Y* show a 9% difference in intensity reflectance

Summary for this telescope (2)

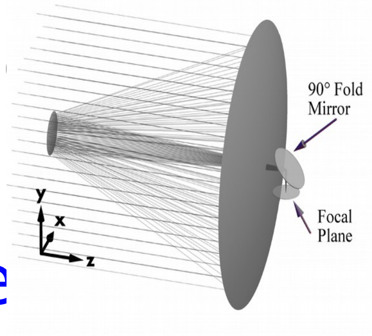


- Light coupled from one polarization forms a separate faint and much larger PSF not superposed on J_{XX} and the J_{YY}
- => complex field may spill over the edges of a mask that is designed assuming scalar diffraction.
  - Radius of 90% encircled energy:

$$r_{XX} = r_{YY} = 0.15 \text{ arcsec and}$$

$$r_{XY} = r_{YX} = 0.36 \text{ arcsec}$$

Summary for this telescope



- Unpolarized sources exit partially polarize
  an instrument.
- The telescope coatings cause polarization variations throughout the PSF, particularly into the diffraction rings to complicate polarization measurements of exoplanets and debris rings in coronagraphs.
- **The Stokes parameters change across the PSF**

New work

- Measure the polarization reflectivity anisotropy and its spatial scale on a large astronomical telescope mirror
- Select a practical coronagraph design and calculate contrast using vector wavefronts
- Refine models to calculate vector diffraction around masks and stops
- Once we have contrast = *f*(polarization), then search for practical mitigation approaches

New work

- Develop a coronagraph test bed that emulates a practical system, measure the polarization aberrations and validate the models
- Explore a spatially variable wave plate which will correct “as-built” telescope systems.
- How much internal polarization can we have and still achieve the 10^{-10} raw contrast needed for terrestrial exoplanets?
- Determine the requirements on the physical properties of the surfaces, # of mirrors, angles, masks, transmittance, etc.
- Design and develop masks and stops to optimize terrestrial exoplanet characterization in the presence of polarization aberrations

Thank you

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