National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

WFIRST-C Polarization (cycle 6)

Jim McGuire

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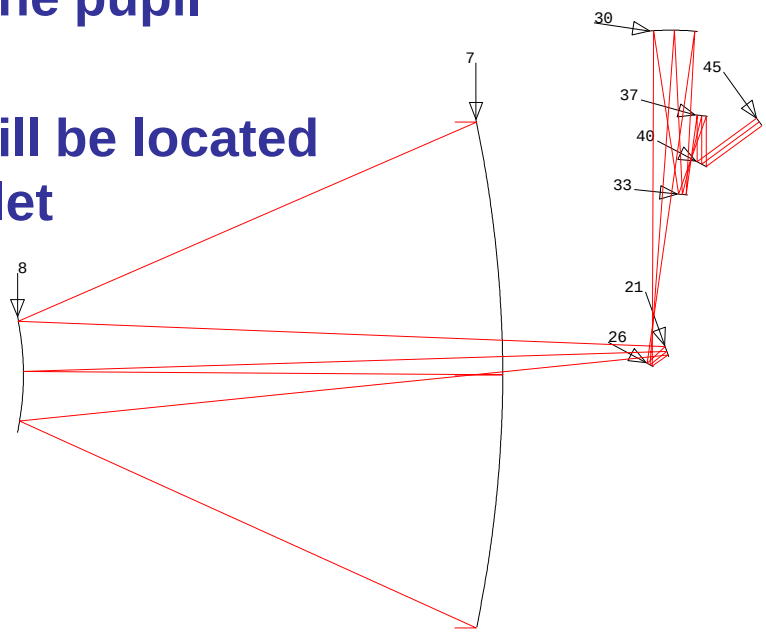
Outline

- Introduction
- Coatings
- Polarization dependent apodization
- Polarization dependent phase
- Polarization aberrations and the coronagraph
- Conclusions

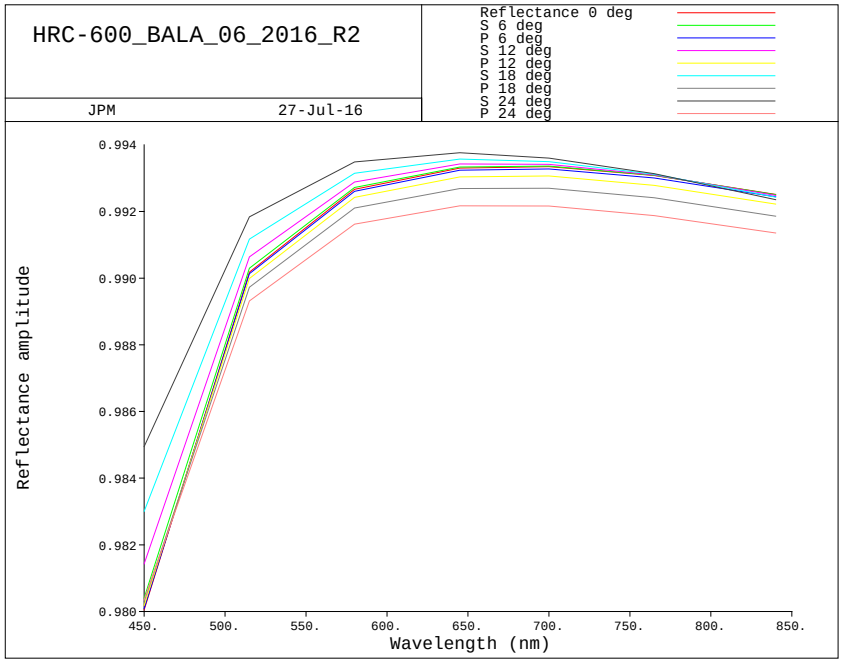
Model

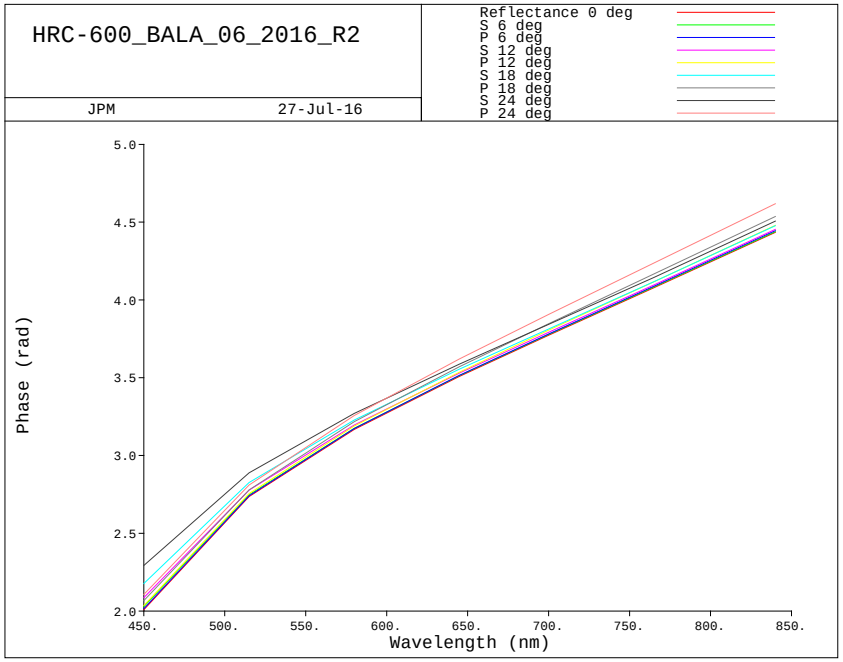
- **Mike Rud translated**
  - Zemax design (AFTA COR V6-6-4)
  - Zemax TXT coatings catalog
    - HRC on primary and secondary (La_2O_3 and MgF_2 coated Ag)
    - FS99-600 on all other reflective surfaces (HfO_2 and
    - SiO_2 coated Ag)
- **Polarization only calculated through the pupil located before the FSM**
- **Polarizer (not present in the model) will be located immediately before the imaging doublet**



HRC Coating

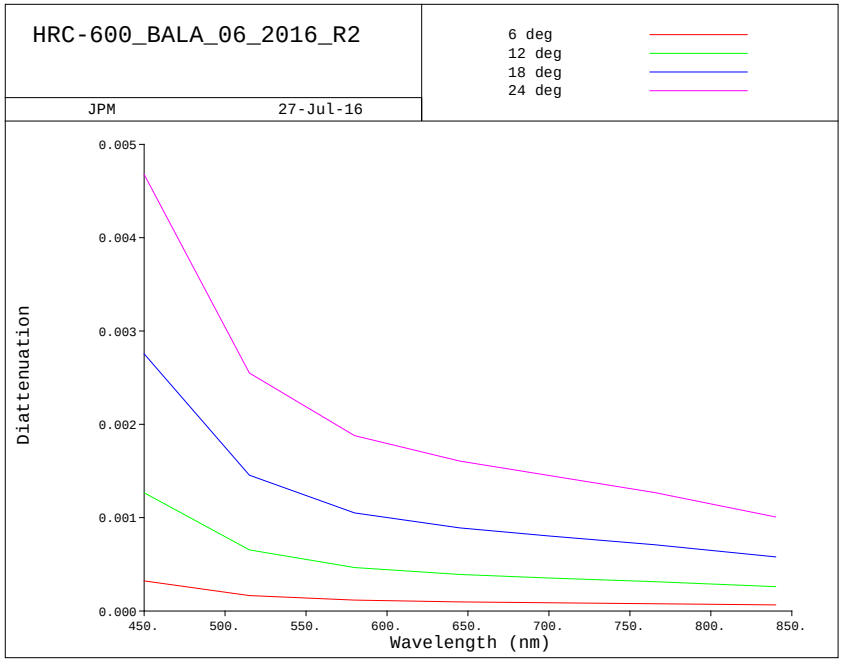
- **Amplitude and phase are**
  - different for s and p-polarized light
  - vary with angle of incidence and polarization

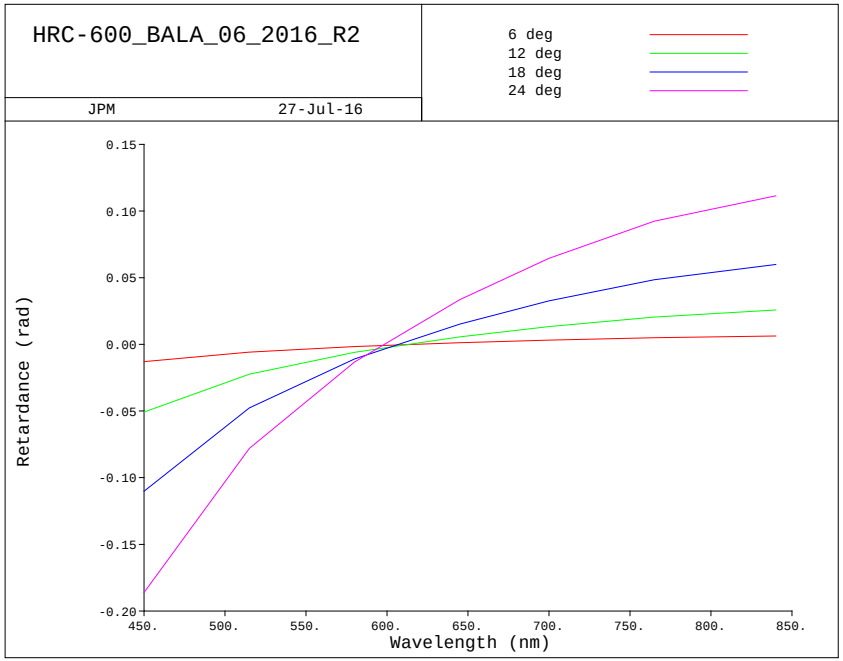




HRC polarization

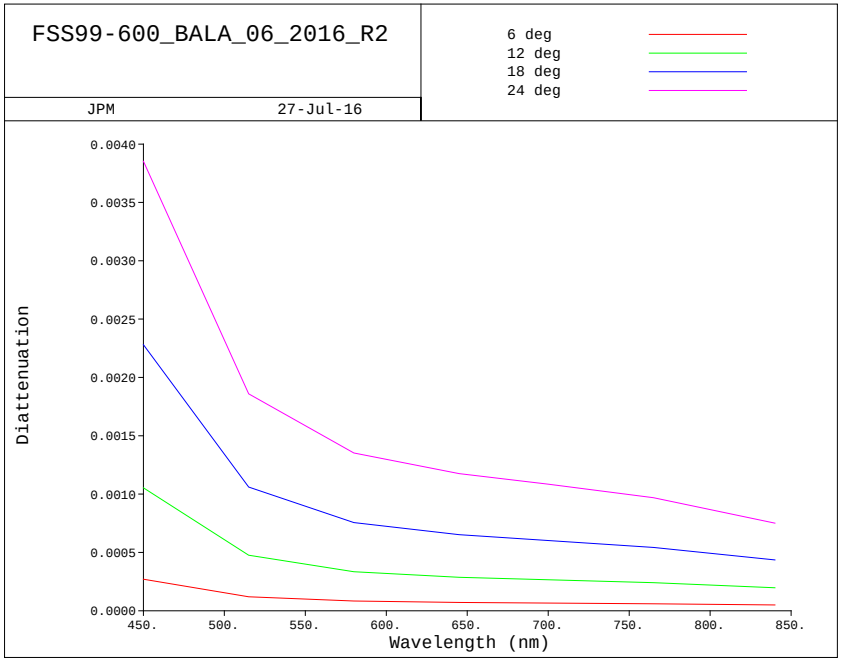
- Diattenuation (Rs-Rp)/(Rs+Rp), which is a measure of the polarization dependent intensity
- Retardance (φs- φp), which is a measure of the polarization dependent phase
- For small values, diattenuation and retardance in radians have comparable effects on the PSF, so we see the retardance aberrations are about 40x more important than diattenuation in the coronagraph

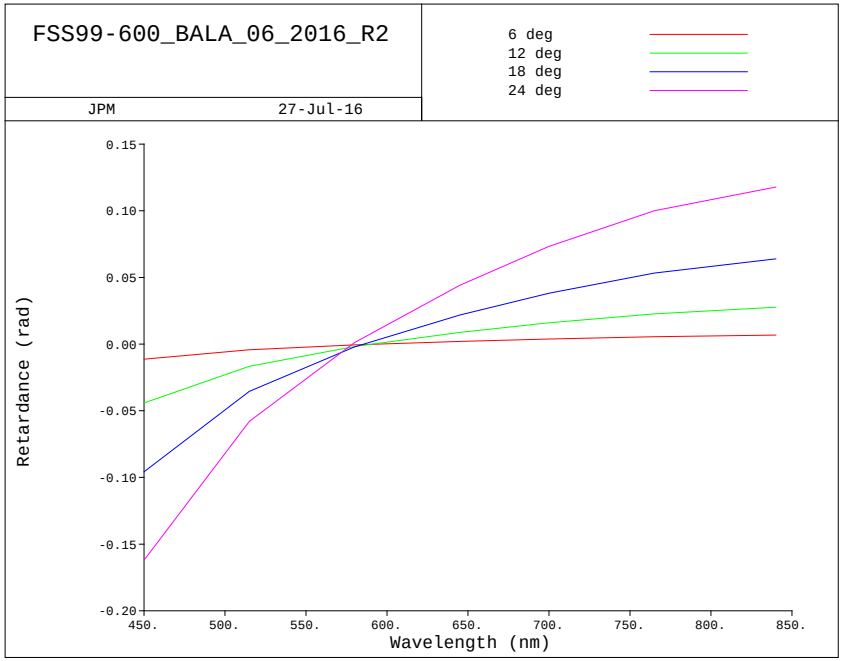




FS99-600 polarization

- **Slightly improved performance**

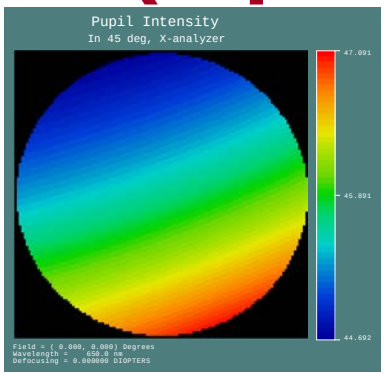




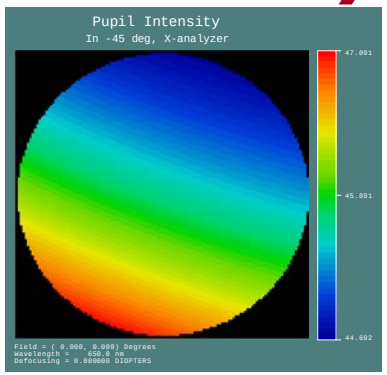
Input polarization

- Unpolarized light can be viewed as a random mixture of 2 orthogonally polarizations
- We choose +45º and -45º linearly polarized input for analysis convenience
- Because of the optical system is (weakly) polarizing, a small portion of the light is coupled into the polarization orthogonal to the input polarization

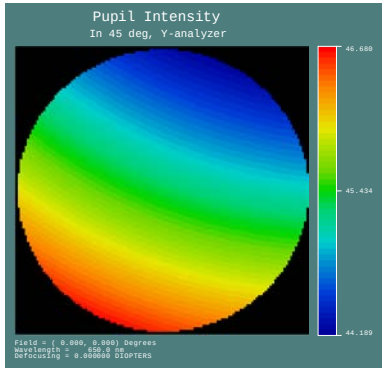
Intensity at 650 nm (input polarized ±45°)



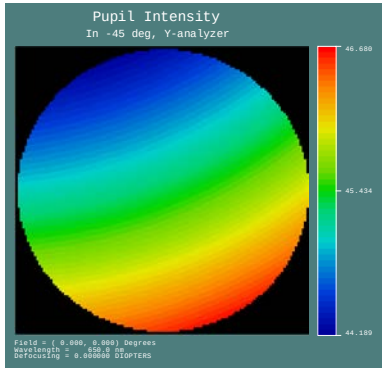
+45° /X polarizer
(44.692% to 47.091%)



-45° /X polarizer
(44.692% to 47.091%)



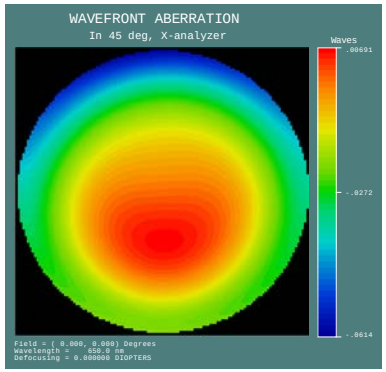
+45° /Y polarizer
(44.189% to 46.680%)



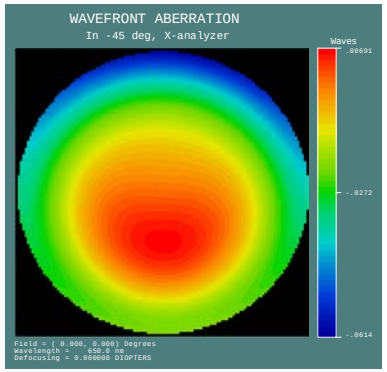
-45° /Y polarizer
(44.189% to 46.680%)

Mirror symmetric

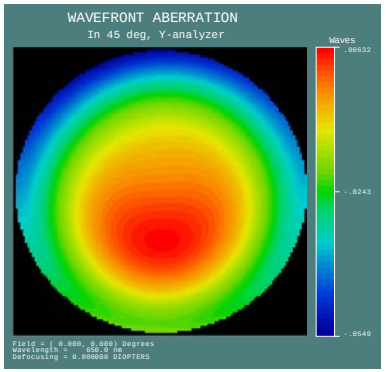
Phases at 650 nm ±45°



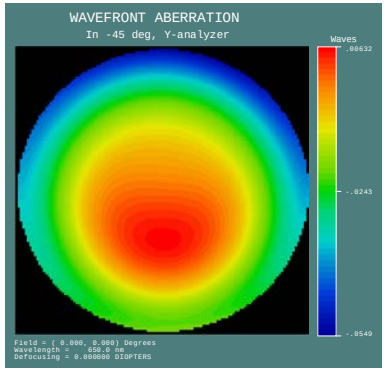
+45° /X polarizer
(-0.0614 to 0.00691 λ)



-45° /X polarizer
(-0.0614 to 0.00691 λ)



+45° /Y polarizer
(-0.0549 to 0.00632 λ)



-45° /Y polarizer
(-0.0549 to 0.00632 λ)

Mirror symmetric.
Largest component is polarization independent phase.

Jones Matrix

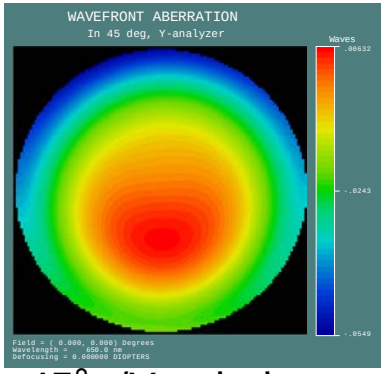
- A Jones matrix relates the input polarization in one orthogonal basis set (0,1) to the output polarization in a second orthogonal basis set (a,b)

$$\begin{pmatrix} E_a \\ E_b \end{pmatrix} = \begin{pmatrix} J_{a0} & J_{a1} \\ J_{b0} & J_{b1} \end{pmatrix} \begin{pmatrix} E_0 \\ E_1 \end{pmatrix}$$

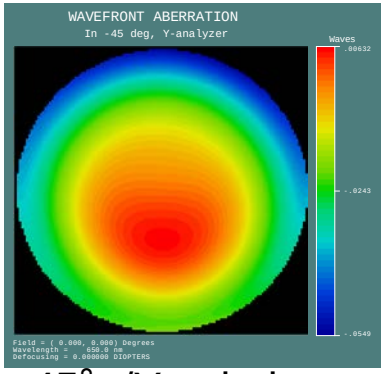
- Each element of the Jones matrix is a complex number
- A non-scattering optical system can be represented by a Jones matrix, with each element of the matrix being a function of the pupil, field, and wavelength

DM Correction

- With the 2 deformable mirrors in the coronagraph, we can compensate for the average intensity and phase variation across all maps over the spectral band (2 of the 8 degrees of freedom in a Jones matrix)
- The addition of a polarizer halves the number of unique terms in the Jones matrix. For example, we could choose a y-polarizer so only the bottom row of the Jones matrix is non-zero (assuming the polarizer is perfect).
- Because of the ±45° input polarization choice and the coronagraph symmetry, each row of the Jones matrix has the same magnitude of variation, but the orientation is mirror symmetric about the y-axis.
- Figures below show the phases through a y-polarizer for +45° and -45° incident polarizations



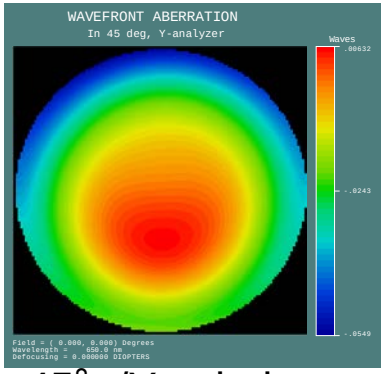
+45° /Y polarizer
(-0.0532 to 0.0055 λ)



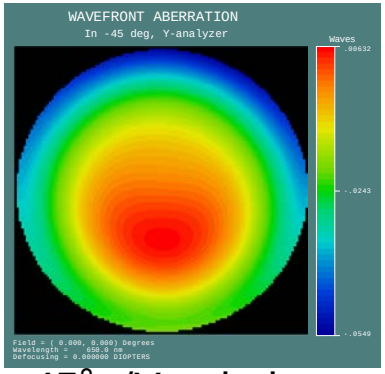
-45° /Y polarizer
(-0.0532 to 0.0055 λ)

Incident polarization

- **The wavefront will need a different correction depending on the incident polarization state (the pictures below show the corrections for +45º and -45º, but any other polarization can be written as a linear combination of this basis state)**
- **If all the photons incident on the telescope had identical polarization, then the DM could perfectly compensate for the wavefront aberrations with the right choice of polarizer.**
- **However, most of the light will be unpolarized (i.e. half +45º which need the correction on the LHS and half -45º with the correction on the RHS), so the best we can do is to correct for the wavefront error that is common for both incident polarizations**



+45° /Y polarizer
(-0.0532 to 0.0055 λ)

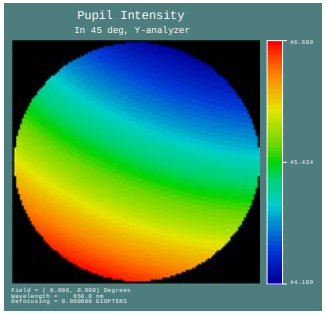


-45° /Y polarizer
(-0.0532 to 0.0055 λ)

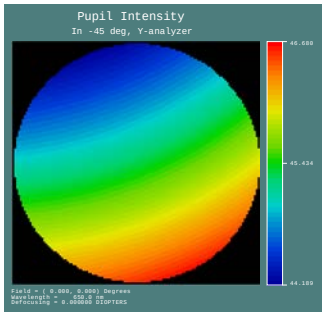
DM residuals

- **The DMs <u>can</u> compensate for the <u>common</u> component between the cases of +45° incident polarization and -45° polarization.**
- **The DMs <u>cannot</u> compensate the <u>difference</u> between the cases of +45° incident polarization and -45° polarization**

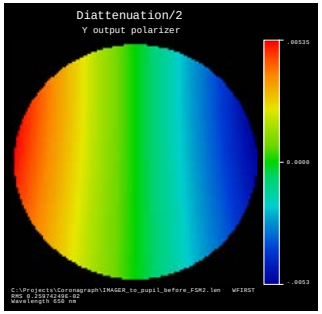
Intensities



+45° /Y polarizer
(44.189% to 46.680%)

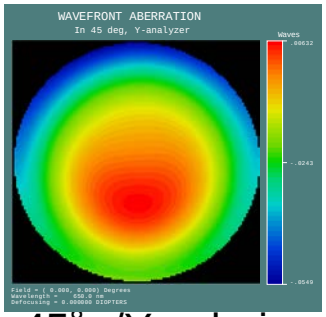


-45° /Y polarizer
(44.189% to 46.680%)

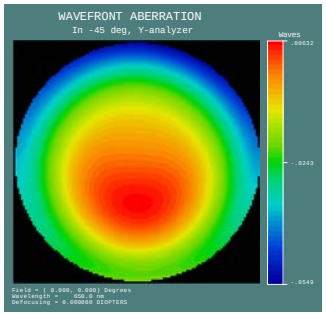


Non-compensable
difference (3e-3 rms)

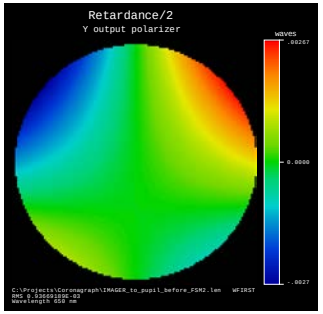
Phases



+45° /Y polarizer
(-0.0532 to 0.0055 λ)

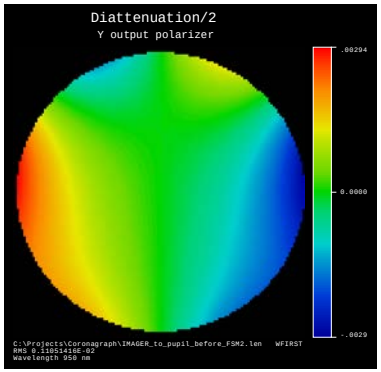
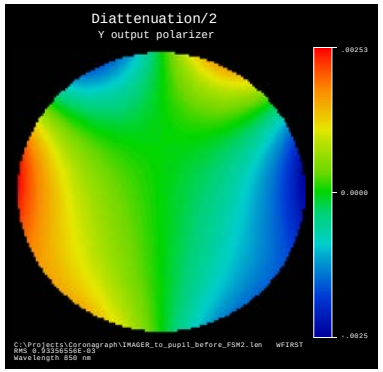
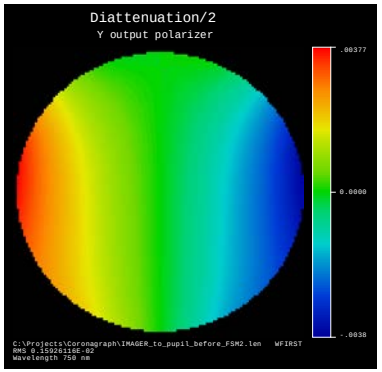
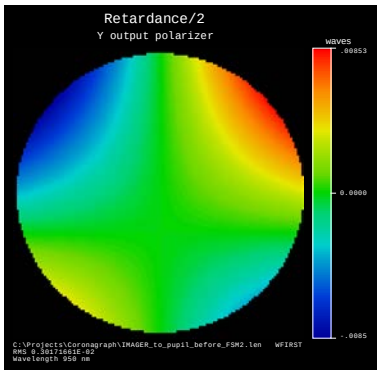
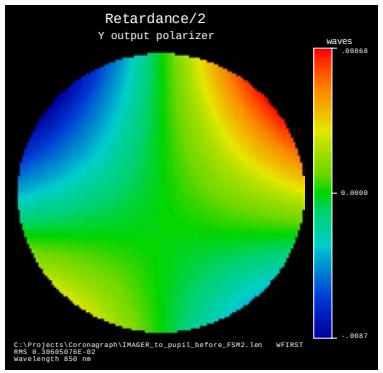
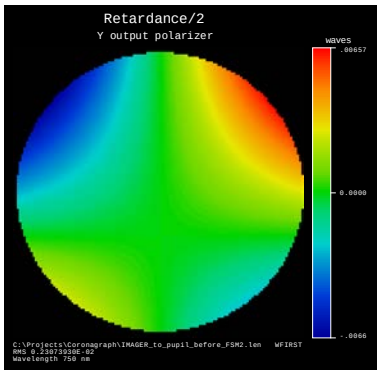


-45° /Y polarizer
(-0.0532 to 0.0055 λ)



Non-compensable
difference (0.9 mλ rms)

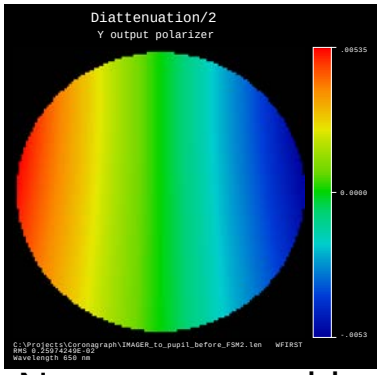
Non-compensable differences

	950 nm	850 nm	750 nm
Intensities			
	Non-compensable difference (1.1e-3 rms)	Non-compensable difference (0.9e-3 rms)	Non-compensable difference (1.6e-3 rms)
Phases			
	Non-compensable difference 3.0 mλ rms)	Non-compensable difference (3.1 mλ rms)	Non-compensable difference (2.3 mλ rms)

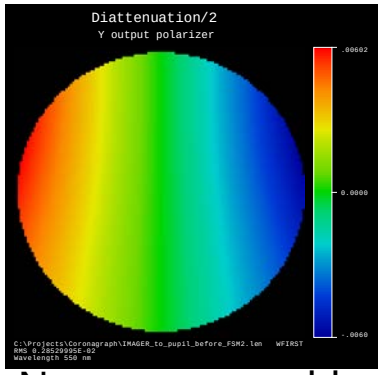
More non-compensable differences

650 nm | 550 nm | 450 nm

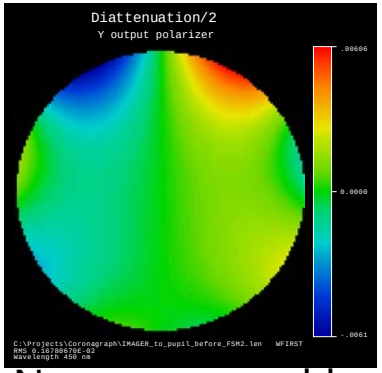
Intensities



Non-compensable difference (2.6e-3 rms)

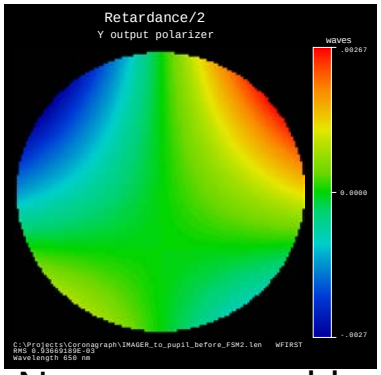


Non-compensable difference (2.9e-3 rms)

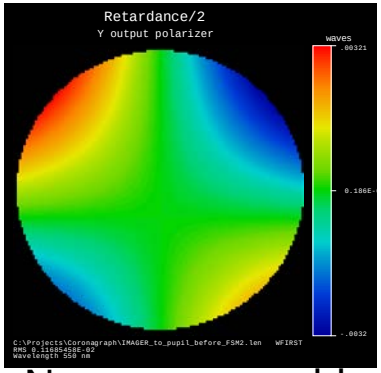


Non-compensable difference (1.7e-3 rms)

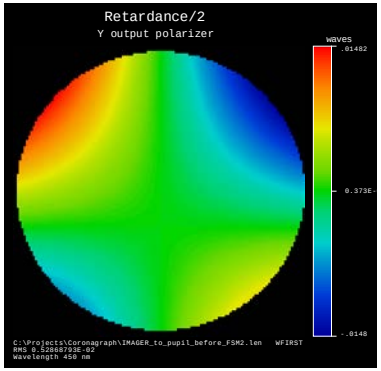
Phases



Non-compensable difference (0.94 mλ rms)



Non-compensable difference (1.2 mλ rms)



Non-compensable difference (5.3 mλ rms)

Conclusions

- **We have computed polarized pupil maps for the coronagraph up to the FSM**
- **Polarization aberrations are low order**
- **Retardance is more important than diattenuation**
- **These simulations did not include**
  - Layer and index errors in coating deposition
  - Stress birefringence in the coatings
  - Polarization of the coatings after the coronagraph
  - Polarization from small features in the coronagraph (e.g. field mask)
  - Scatter from coatings, dust on the coatings, or high spatial frequency errors in the mirrors (most of the light will be scattered outside the coronagraph field).

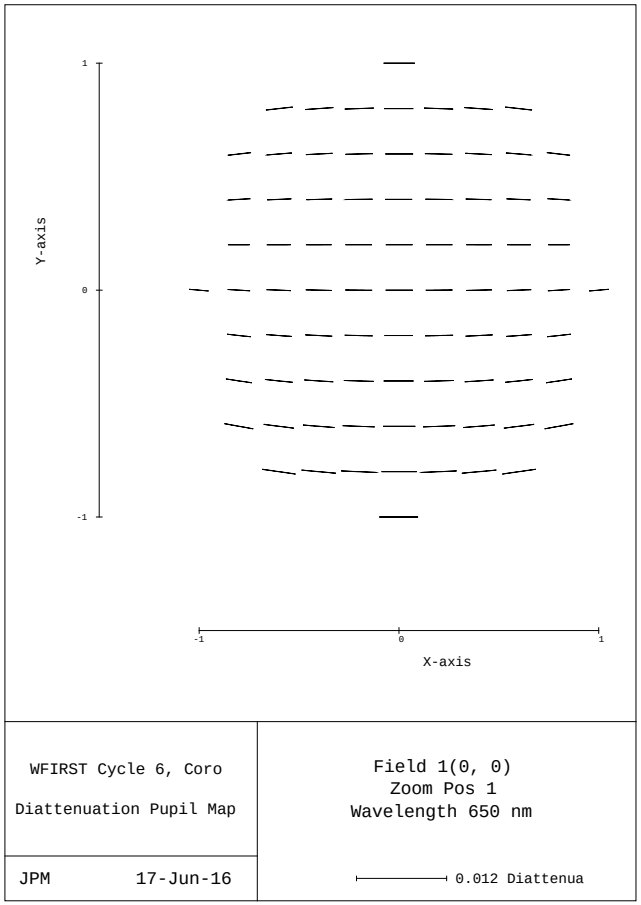
BACKUP SLIDES

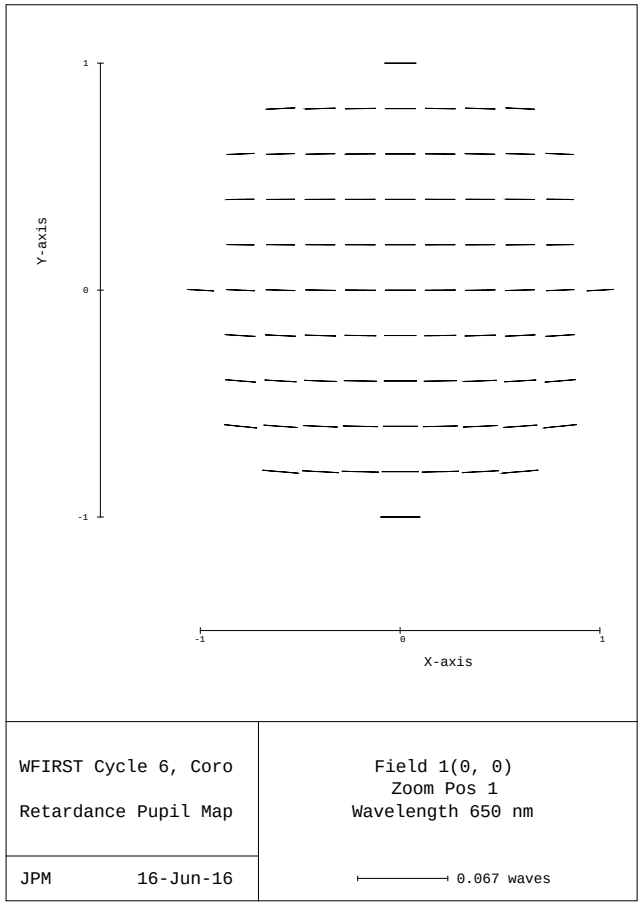
Polarization diagrams

- **Instead of looking at the effect of the polarization aberrations (variations in the retardance and diattenuation across the pupil) on an arbitrary input polarization state, it can be more informative to look at the aberrations themselves.**
- **For these displays,**
  - The shape of the symbol denotes the shape of the retardance or diattenuation (a linear retarder would be a line and an elliptical retarder would be elliptical)
  - The size of the symbol indicates the strength of the aberration
  - The orientation of the symbol indicates the orientation of the aberration
- **The polarizer is <u>not</u> included in the following calculations**

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Polarization aberrations at 650 nm

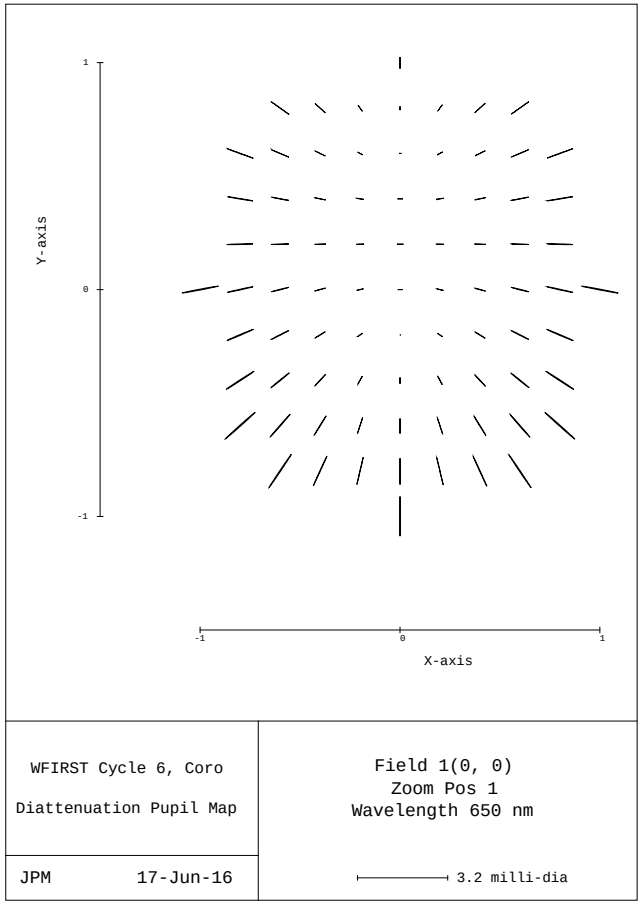


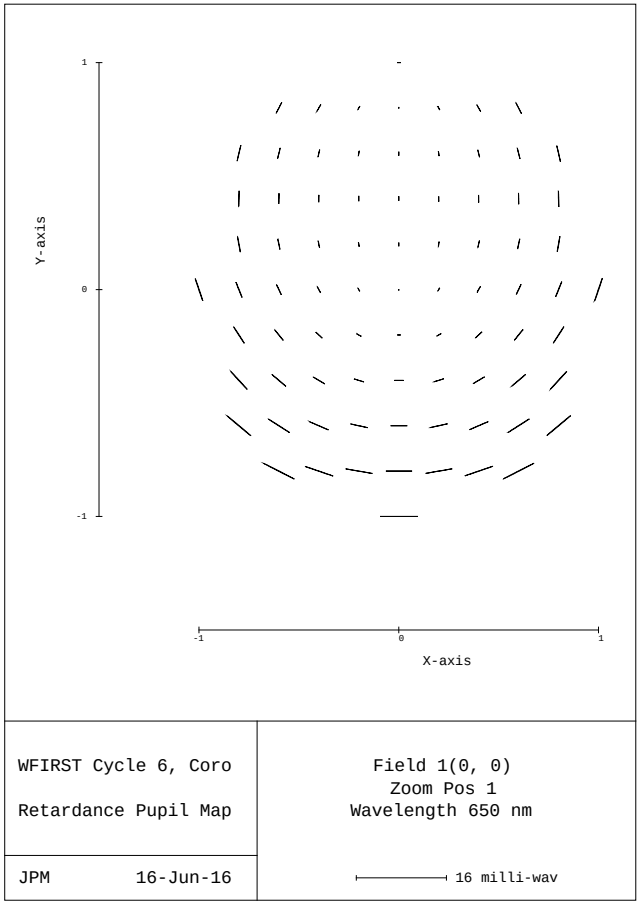


Diattenuation < 0.0051 Retardance < 0.029 λ

The large component that is constant across the pupil (i.e. piston) does not effect coronagraph performance

Polarization aberrations at 650 nm *minus piston*





Diattenuation
0.00141 mag
0.00058 RMS

Retardance (λ)
0.00665 mag
0.00242 RMS

Diattenuation

- The diattenuation, (max-min)/(max+min), describes the maximum change in illumination contrast at each point in the pupil.
- A single DM can adjust the illumination to the compensate for the average illumination, so the residual error would be about ½ the diattenuation.

					Piston removed	
Zoom	Field	Wavelength	Maximum Magnitude	RMS	Maximum Magnitude	RMS
1	1	950.000	0.00102	0.00018	0.00097	0.00018
1	1	850.000	0.00313	0.00035	0.00126	0.00033
1	1	750.000	0.00435	0.00047	0.00130	0.00045
1	1	650.000	0.00512	0.00056	0.00141	0.00058
1	1	550.000	0.00669	0.00075	0.00213	0.00084
1	1	450.000	0.01678	0.00184	0.00579	0.00232

Retardance

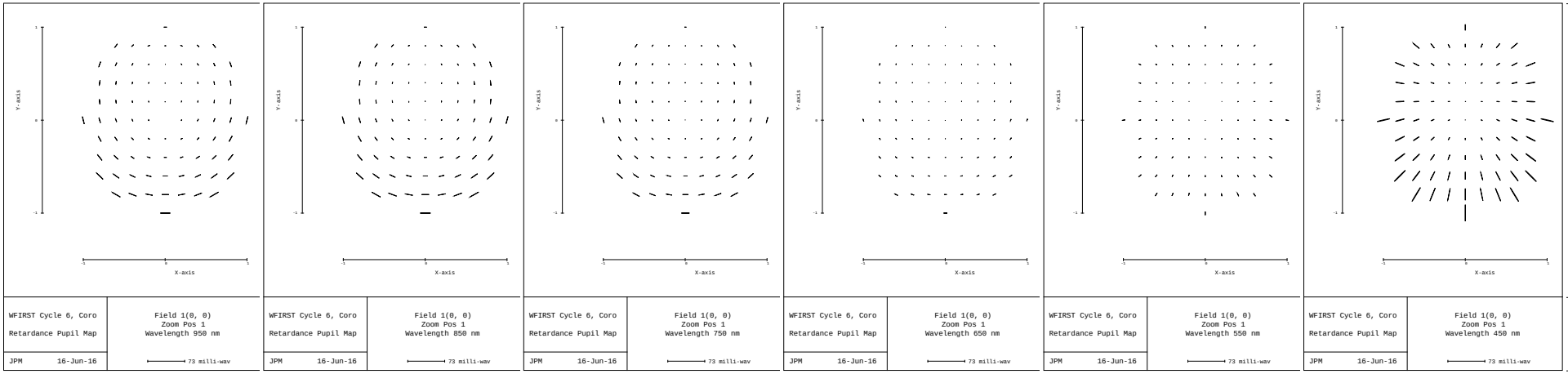
- **The retardance describes the maximum change in the wavefront for any input polarization.**
- **A single DM can adjust the phases to the compensate for the average wavefront, so the residual error would be about ½ the retardance.**

					Piston removed	
Zoom	Field	Wavelength	Maximum Magnitude	RMS	Maximum Magnitude	RMS
1	1	950.000	0.07196	0.00681	0.01909	0.00748
1	1	850.000	0.07760	0.00700	0.01995	0.00767
1	1	750.000	0.06127	0.00533	0.01537	0.00581
1	1	650.000	0.02941	0.00224	0.00665	0.00242
1	1	550.000	0.01777	0.01176	0.00649	0.00281
1	1	450.000	0.11123	0.07999	0.03221	0.01304

RMS changes by almost a factor of 4 with piston removal. RMS values are not expected to change “much” under the low polarization assumption used for piston removal, so there is a bug in my understanding or code.

Retardance minus piston vs Wavelength

- Plots have the same scale
- The sign of the retardance aberrations changes between 550 and 650 nm.



Need to correct the retardance aberrations over the entire spectral band

Rest of the system

- **These slides examined the polarization before the FSM.**
- **The angles of incidence (AOI) give some insight into the magnitude of the problem in the rest of the system, since the polarization goes as the square of the AOI for small angles.**
  - Variation across the pupil (maximum angle – center angle) is approximately much lower.
  - Focusing mirror is the worst contributor in the coronagraph with an AOI variation about 1/6th the telescope primary and secondary (1/36th the polarization aberration).

Surface Number	Label	Angle of incidence Maximum	Maximum-Center
7	T1	12.3	11.868
8	T2	14.9	13.857
21	COR F1	22.2	3.989
26	COR F2	27.7	3.978
30	M3	4.5	0.991
33	COL F1	14.3	5.959
37	M4	9.9	2.980
40	COL F2	27.0	0.000
46	FSM	27.0	0.000
54	R1 OAP1	6.0	1.028
58	Focusing mirror	6.1	2.056
64	R1 OAP2	6.0	1.028
67	DM1	4.0	0.000
71	DM2	7.0	0.000
75	R2 OAP1	7.1	0.640
79	FM	5.2	1.279
83	R2 OAP2	7.1	0.639
86	SP-Mask/HLC-FM	6.0	0.000
92	R3 OAP1	6.3	0.437
101	R3 OAP2	6.3	0.436
111	FS-OAP1	5.0	0.242
120	FS-OAP2	5.0	0.241
133	Imaging f=562	0.5	0.492
134		0.7	0.661
135		0.2	0.205
137	Imgr Rad Shield	20.2	0.249

Reducing impact of polarization aberrations

- **Use a polarizer.**
  - The coronagraph testbeds have demonstrated that this approach is effective for minimizing the effect of polarization within the coronagraph, at the price of half the light.
  - Unfortunately, the polarization aberrations from the telescope are much larger than in the current testbed (proportional to roughly the angle of incidence squared).
- **Optimize the coatings**
  - Coatings are sometimes applied with a non-uniform thickness. Bala reduced the polarization of TPF-C using coatings with the overcoats on some surfaces thinner than “optimum” and others thicker than “optimum” to reduce the polarization signature.
  - Mitigate angle of incidence effects. This would probably be more leveraged in the telescope (where it is harder to implement)
- **Insert spatially varying retarder**
  - The sign of the retardance varies across the 450-950 nm spectral band, which may be challenging to duplicate. A different spatially varying retarder may be needed for each spectral band. The variation over the each filter’s bandpass will need to be taken into account
  - Variable thickness birefringent plate (crystal axis along the optical axis)
  - Tunable stress birefringent plate (one could be used for multiple wavelengths)
  - Sub-wavelength structures

Spatially varying retarders are the most promising option

Next Steps

- Design uniaxial crystal compensators in CODE V (in process)
- Compile user-defined surface properties for coatings in CODE V
- Optimize primary and secondary coating individual layer thicknesses
- Model the polarization in the testbed coronagraph
- Model physical optics (i.e. diffraction) with polarization through the entire coronagraph in CODE V