Modeling optics perturbations in GalSim

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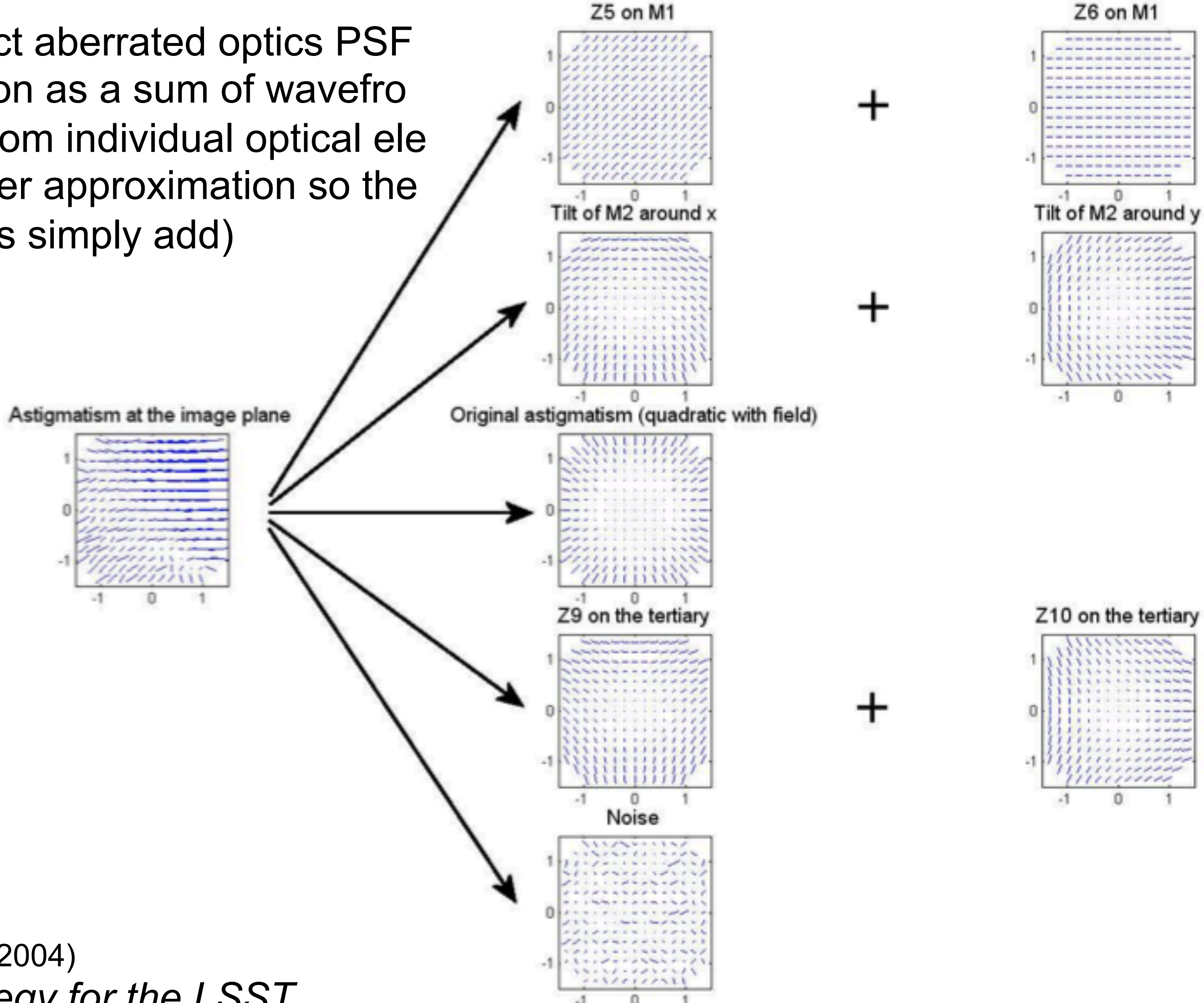
Outline

- The semi-analytic model for optics perturbations
  - Model framework
  - Required calibrations from ZEMAX
- How GalSim renders aberrated optics PSFs
- Interface with ‘phase_psf’ created for the atmosphere

Main idea: Predict aberrated optics PSF at any field location as a sum of wavefro nt contributions from individual optical ele ments (Fraunhofer approximation so the wavefront phases simply add)



Tessieres & Burge (2004)

Alignment strategy for the LSST

Figure IV.1: Decomposition of the astigmatism into particular field dependent aberrations.

Modeling misalignments of optics

- The wavefront can be series expanded in powers of the pupil coordinate, rho, and field coordinate, H:

$$W(\vec{H},\vec{\rho}) = \sum_{i=1}^{n_{\text{surfaces}}} \sum_{p=0}^{\infty} \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} W_{k\ell m,i} \left(\vec{H}\cdot\vec{H}\right)^{p} (\vec{\rho}\cdot\vec{\rho})^{n} \left(\vec{H}\cdot\vec{\rho}\right)^{m}$$

- For a perturbed system, the field coordinates get remapped:

$$\vec{H}_i = \vec{H} - \vec{\sigma}_i$$

Model parameters

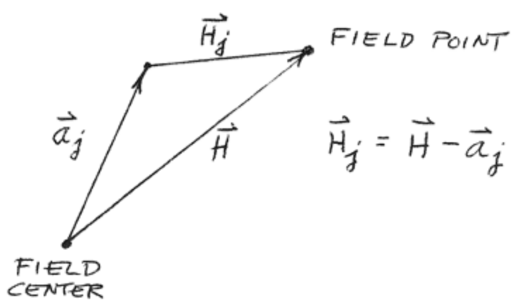
  - Work out cross terms and reorganize -> new lower order terms produced.

Get the $W_{k\ell m,i}$ coefficients from a Zemax model.

From Thompson: Effects of tilts/decenters

In a centered optical system the total aberration is given by the sum of the individual surface contributions. Each of the surface contributions is rotationally symmetric about the center of its field, and all of the centers are coincident at the axial field point, resulting in the total aberration being also rotationally symmetric about that point.

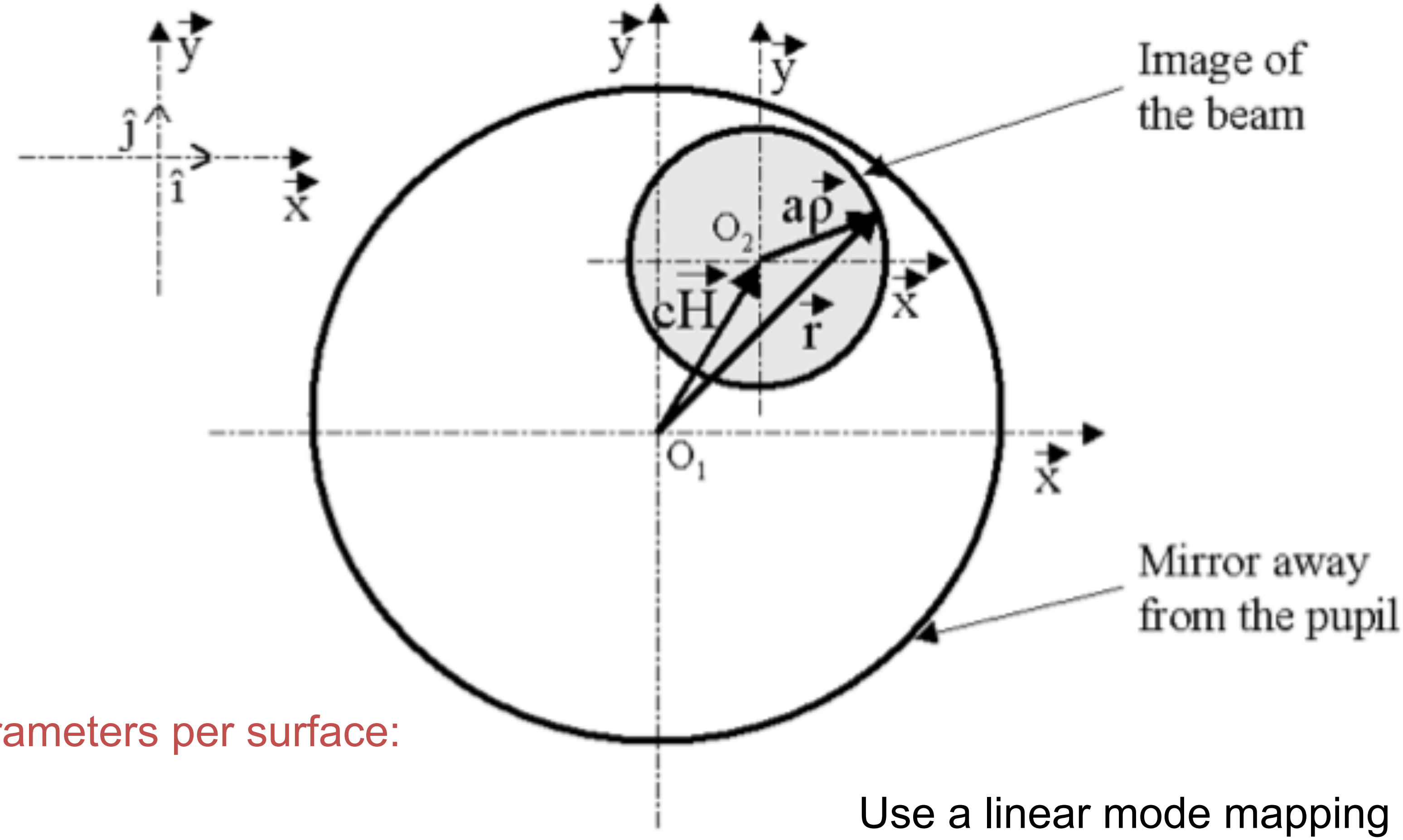
When the system is perturbed by tilts and decenters, the principal effect is the displacement of the aberration field centers of the surface contributions, which in general are no longer coincident in the field. Nevertheless, they are individually very little altered except for the above displacement, and the total aberration is still their summat Relative to the point which is chosen to be the center of th field, the individual aberration field centers are located by position vectors a_j:



$$\vec{H}_j = \vec{H} - \vec{a}_j$$

Geometry for mapping bending modes on mirrors to basis functions in the exit pupil

An off-axis source illuminates a fraction of the optical surfaces further along the optical path.



2 parameters per surface:
a, c

Use a linear mode mapping matrix

Model parameters

- 8 Zernike terms on each of M1/M3 and M2 for a total of 16 bending mode parameters
  - Defocus, astigmatism (1,2), coma (1,2), trefoil (1,2), spherical aberration
- 2 image plane displacements (x, y) mapped from tilts and decenters of:
  - Secondary, L1, L2, L3
  - 8 parameters total
- Combined: 24 optics perturbation parameters

ZEMAX calibrated parameters

- W_klm
  - Scripted by A. Roodman
  - Require jointly orthogonal Zernikes in field and pupil coordinates to remove sensitivity to the order of truncation of the series expansion
- (a,c) for each surface
  - M2, M3
- (Correlated) distributions of bending mode coefficients
- Distributions of reasonable tilts and decenters for each optic

Double Zernikes: Are all terms physical?

- Consider linear combinations of products of Zernikes so that the standard aberrations can be matched to a single term (page 169 of Manuel thesis),

-

$$Z_k(h,\theta)Z_i(\rho,\phi) + Z_l(h,\theta)Z_j(\rho,\phi),$$

$$Z_k(h,\theta)Z_i(\rho,\phi) - Z_l(h,\theta)Z_j(\rho,\phi),$$

$$Z_l(h,\theta)Z_i(\rho,\phi) + Z_k(h,\theta)Z_j(\rho,\phi), \text{ and}$$

$$Z_l(h,\theta)Z_i(\rho,\phi) - Z_k(h,\theta)Z_j(\rho,\phi),$$

- From Manuel's thesis (end of section 6.6 - page 170):

- The functions to complete the basis that are not listed in Section 6.5 may still be possible due to misalignments. However, the terms not listed are expected to be very small. By considering increasingly higher orders of field dependencies (more $\vec{H} \cdot \vec{H}$ terms so the first subscript of the aberration increases by two: W222, W422, W622 etc. for the case of astigmatism), it is possible to create any of the functions throughout the field in the entire basis for any given aberration.

"Subspace of benign misalignment"

- Schechter & Levinson (2011) identify that for a "three mirror anastigmat" there is a subspace of benign misalignments where 3rd order perturbations cancel.
  - — - No need for AO to correct beyond 3rd order?
  - — - What do 5th order (and higher) residuals impart to the ellipticity correlations?
  - — *"… a small relative error in a measurement of a third-order aberration pattern will produce a large relative error in the corresponding fifth-order aberration pattern."*

  - — Could be a blind spot in the LSST AO control, or just an artifact of non-orthogonal basis functions (in field coordinates).

Allowed mis-alignments: Kwee & Braat (1993)

Table 1. Aberration coefficients.

No	Aberration type	$X_{nm}x_{lk}$	R_{nm}	ϕ	R_{lk}	θ	1a	1b	2	r
1	x shift	$A_{11}a_{00}$	ρ	$\cos\phi$	1		x	—	—	—
2	Magnification change	$A_{11}a_{11}$	ρ	$\cos\phi$	η	$\cos\theta$	x	x	x	◇
3	Rhomb distortion	$A_{11}b_{11}$	ρ	$\cos\phi$	η	$\sin\theta$	—	—	—	—
4	Image torsion	$A_{11}a_{20}$	ρ	$\cos\phi$	$2\eta^2-1$		x	—	—	—
5	Image bending	$A_{11}a_{22}$	ρ	$\cos\phi$	η^2	$\cos 2\theta$	x	—	—	—
6	Keystone (wedge)	$A_{11}b_{22}$	ρ	$\cos\phi$	η^2	$\sin 2\theta$	—	x	—	—
7	Pincushion/barrel	$A_{11}a_{31}$	ρ	$\cos\phi$	$3\eta^3-2\eta$	$\cos\theta$	x	x	x	△
8	Sigma distortion	$A_{11}b_{31}$	ρ	$\cos\phi$	$3\eta^3-2\eta$	$\sin\theta$	—	—	—	—
9	Trefoil distortion A	$A_{11}a_{33}$	ρ	$\cos\phi$	η^3	$\cos(3\theta)$	x	x	x	—
10	Trefoil distortion B	$A_{11}b_{33}$	ρ	$\cos\phi$	η^3	$\sin(3\theta)$	—	—	—	—
11	y shift	$B_{11}a_{00}$	ρ	$\sin\phi$	1		—	x	—	—
12	Rhomb distortion	$B_{11}a_{11}$	ρ	$\sin\phi$	η	$\cos\theta$	—	—	—	—
13	Magnification change	$B_{11}b_{11}$	ρ	$\sin\phi$	η	$\sin\theta$	x	x	x	◇
14	Image torsion	$B_{11}a_{20}$	ρ	$\sin\phi$	$2\eta^2-1$		—	x	—	—
15	Keystone (wedge)	$B_{11}a_{22}$	ρ	$\sin\phi$	η^2	$\cos 2\theta$	—	x	—	—
16	Image bending	$B_{11}b_{22}$	ρ	$\sin\phi$	η^2	$\sin 2\theta$	x	—	—	—
17	Sigma distortion	$B_{11}a_{31}$	ρ	$\sin\phi$	$3\eta^3-2\eta$	$\cos\theta$	—	—	—	—
18	Pincushion/barrel	$B_{11}b_{31}$	ρ	$\sin\phi$	$3\eta^3-2\eta$	$\sin\theta$	x	x	x	△
19	Trefoil distortion B	$B_{11}a_{33}$	ρ	$\sin\phi$	η^3	$\cos(3\theta)$	—	—	—	—
20	Trefoil distortion A	$B_{11}b_{33}$	ρ	$\sin\phi$	η^3	$\sin(3\theta)$	x	x	x	—
21	Focus shift	$A_{20}a_{00}$	$2\rho^2-1$		1		x	x	x	x
22	x-tilt focal plane	$A_{20}a_{11}$	$2\rho^2-1$		η	$\cos\theta$	x	—	—	—
23	y-tilt focal plane	$A_{20}b_{11}$	$2\rho^2-1$		η	$\sin\theta$	—	x	—	—
24	Field curvature	$A_{20}a_{20}$	$2\rho^2-1$		$2\eta^2-1$		x	x	x	x
25	Astigmatic curvature	$A_{20}a_{22}$	$2\rho^2-1$		η^2	$\cos 2\theta$	x	x	x	—
26	45° astigmatic curvature	$A_{20}b_{22}$	$2\rho^2-1$		η^2	$\sin 2\theta$	—	—	—	—

Allowed mis-alignments: Kwee & Braat (1993)

Table 1. (continued)

27	Intrinsic astigmatism	$A_{22}a_{00}$	ρ^2	$\cos 2\phi$	1		x	x	x
28	x-linear astigmatism	$A_{22}a_{11}$	ρ^2	$\cos 2\phi$	η	$\cos\theta$	x	—	—
29	y-linear astigmatism	$A_{22}b_{11}$	ρ^2	$\cos 2\phi$	η	$\sin\theta$	—	x	—
30	Spherical astigmatism	$A_{22}a_{20}$	ρ^2	$\cos 2\phi$	$2\eta^2-1$		x	x	x
31	Astigmatic astigmatism	$A_{22}a_{22}$	ρ^2	$\cos 2\phi$	η^2	$\cos 2\theta$	x	x	x
32	45° ast. astigmatism	$A_{22}b_{22}$	ρ^2	$\cos 2\phi$	η^2	$\sin 2\theta$	—	—	—
33	Intrinsic 45° astigmatism	$B_{22}a_{00}$	ρ^2	$\sin 2\phi$	1		—	—	—
34	x-linear 45° astigmatism	$B_{22}a_{11}$	ρ^2	$\sin 2\phi$	η	$\cos\theta$	—	x	—
35	y-linear 45° astigmatism	$B_{22}b_{11}$	ρ^2	$\sin 2\phi$	η	$\sin\theta$	x	x	—
36	Spherical 45° astigmatism	$B_{22}a_{20}$	ρ^2	$\sin 2\phi$	$2\eta^2-1$		—	—	—
37	Astigmatic 45° astigmatism	$B_{22}a_{22}$	ρ^2	$\sin 2\phi$	η^2	$\cos 2\theta$	—	—	—
38	45° ast. 45° astigmatism	$B_{22}b_{22}$	ρ^2	$\sin 2\phi$	η^2	$\sin 2\theta$	x	x	x
39	Intrinsic x-coma	$A_{31}a_{00}$	$3\rho^3-2\rho$	$\cos\phi$	1		x	—	—
40	x-linear x-coma	$A_{31}a_{11}$	$3\rho^3-2\rho$	$\cos\phi$	η	$\cos\theta$	x	x	x
41	y-linear x-coma	$A_{31}b_{11}$	$3\rho^3-2\rho$	$\cos\phi$	η	$\sin\theta$	—	—	—
42	Intrinsic y-coma	$B_{31}a_{00}$	$3\rho^3-2\rho$	$\sin\phi$	1		—	x	—
43	x-linear y-coma	$B_{31}a_{11}$	$3\rho^3-2\rho$	$\sin\phi$	η	$\cos\theta$	—	—	—
44	y-linear y-coma	$B_{31}b_{11}$	$3\rho^3-2\rho$	$\sin\phi$	η	$\sin\theta$	x	x	x
45	Intrinsic x-coma (cubic)	$A_{33}a_{00}$	ρ^3	$\cos 3\phi$	1		x	—	—
46	x-linear x-coma (cubic)	$A_{33}a_{11}$	ρ^3	$\cos 3\phi$	η	$\cos\theta$	x	x	x
47	y-linear x-coma (cubic)	$A_{33}b_{11}$	ρ^3	$\cos 3\phi$	η	$\sin\theta$	—	—	—
48	Intrinsic y-coma (cubic)	$B_{33}a_{00}$	ρ^3	$\sin 3\phi$	1		—	x	—
49	x-linear y-coma (cubic)	$B_{33}a_{11}$	ρ^3	$\sin 3\phi$	η	$\cos\theta$	—	—	—
50	y-linear y-coma (cubic)	$B_{33}b_{11}$	ρ^3	$\sin 3\phi$	η	$\sin\theta$	x	x	x
51	Spherical aberration	$A_{40}a_{00}$	$6\rho^4-6\rho^2+1$		1		x	x	x
52	Quadratic astigmatism	$A_{42}a_{00}$	$4\rho^4-3\rho^2$	$\cos 2\phi$	1		x	x	x
53	Quadratic 45° astigmatism	$B_{42}a_{00}$	$4\rho^4-3\rho^2$	$\sin 2\phi$	1		—	—	—
54	Quartic astigmatism	$A_{44}a_{00}$	$4\rho^4$	$\cos(4\phi)$	1		x	x	x
55	Quartic 45° astigmatism	$B_{44}a_{00}$	$4\rho^4$	$\sin(4\phi)$	1		—	—	—
		Total number of independent aberrations					29	29	20

Limitations

- All aberrations are low-order in both pupil and field coordinates by construction
  - Missing static high frequency terms (Roodman)?
- No despace modeling
- Bending modes not well characterized by low-order Zernike expansion

GalSim aberrated optics PSF

- Specify 3rd order Zernike coefficients for a pupil wavefront
- Construct the wavefront on a grid using Zernike function recursion relation
- Exponentiate and apply pupil mask
- Compute the 2D FFT
- Render on an output image grid of specified scale and size

Implementation of field-dependent aberrations with GalSim

1. Define parameters: Zernike coefficients on each mirror and tilts/decenters mapped to image plane displacements.

2. Map to Zernike coefficients in pupil with the previously described coordinate transforms.

3. Construct pupil wavefront from Zernike coefficients using existing wavefront function

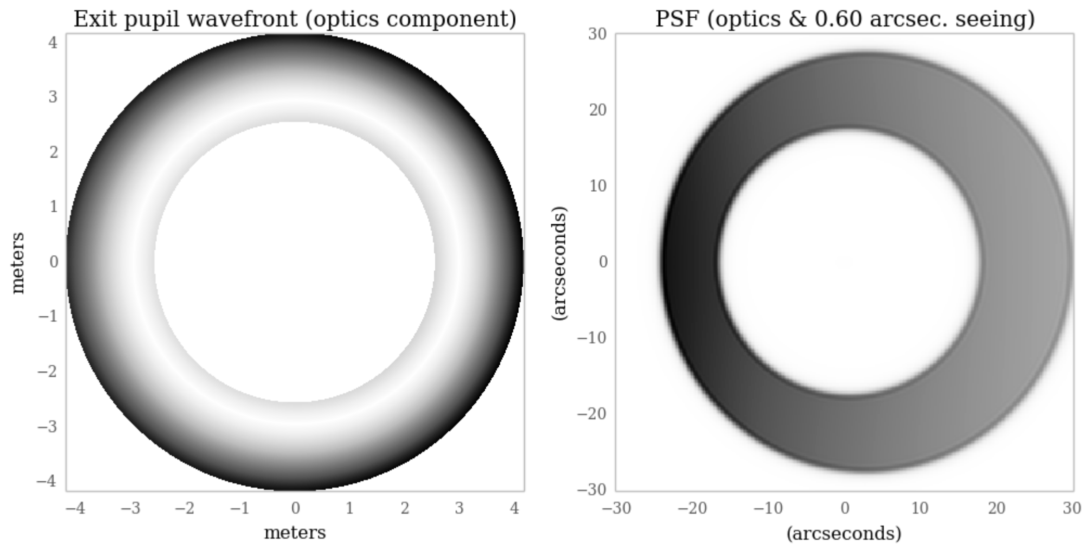
4. Sum the pupil wavefronts from each mirror
   1. This is not strictly correct because the LSST mirrors are not conjugate.
   2. Can do an FFT to propagate each wavefront instead.

5. FFT the combined pupil wavefront to get the PSF in the image plane using existing method

6. Go to step 2 and repeat for each position in the image plane.

See GalSim Issue #716 – Fit into new atmosphere simulator framework by J. Meyers

Direct simulation of the WFS images



Npix = 4096^2
Defocus_mm = 1.0

Image scale: 0.2 (arcseconds)
Image shape: 302, 302

21s to render

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