FIELD NOTES

DAILY DISPATCHES FROM THE SPORTING WORLD

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November 18, 2010

Science Creates The Ultimate Trail Cam...Kinda

The ultimate trail cam, coming soon to a retailer near you, just as soon as engineers can figure out how to strap the 570-megapixel camera to a tree...

From this story on Wired Science:

The world's largest dark energy–hunting device, also one of the biggest, heaviest and highest-resolution cameras in the world, is close to completion. Construction of the 4-ton Dark Energy Camera is wrapping up next month at Fermilab in Illinois, where it's being tested on a mock-up telescope mount.

The Dark Energy Survey hopes to open its $35 million camera for business at its final destination, in the

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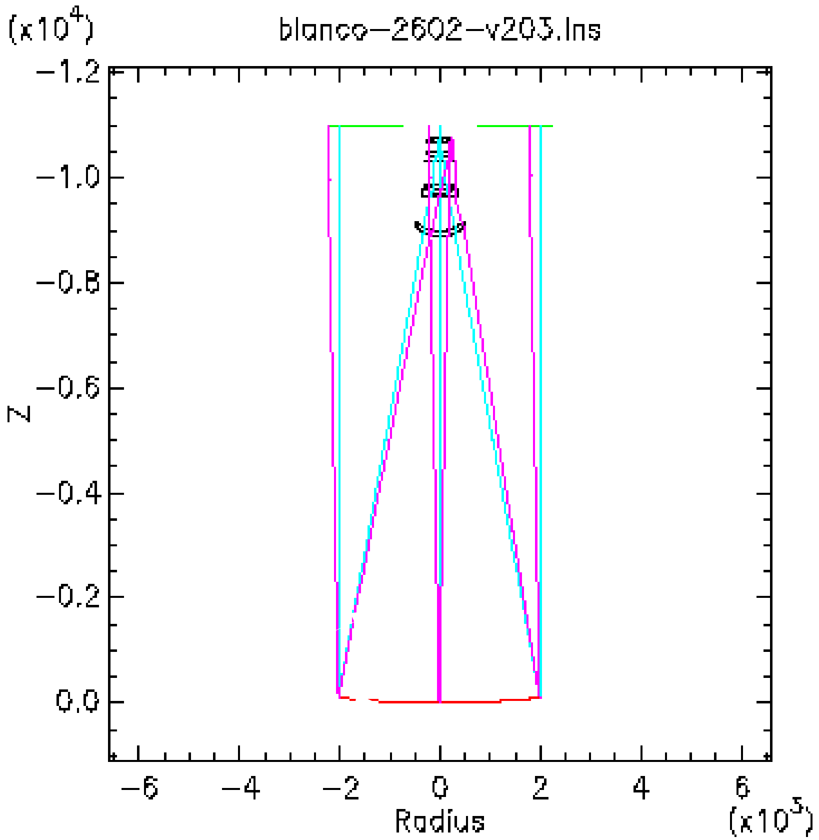
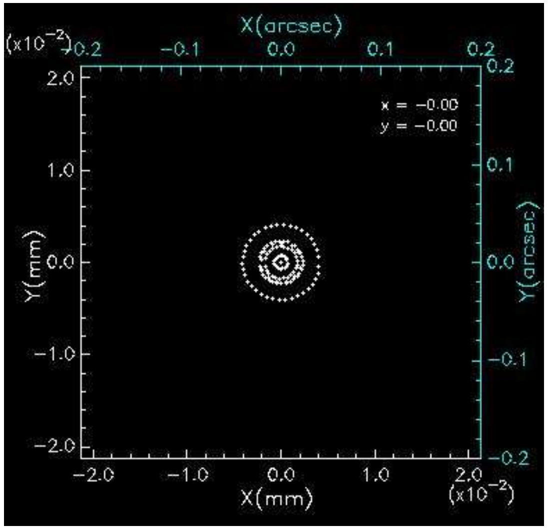
DES/DECam 4-Meter OPTICS

- A. Principles of Telescopes
  - Reference: D. Schroeder, *Astronomical Optics*
- B. Features of 4m design

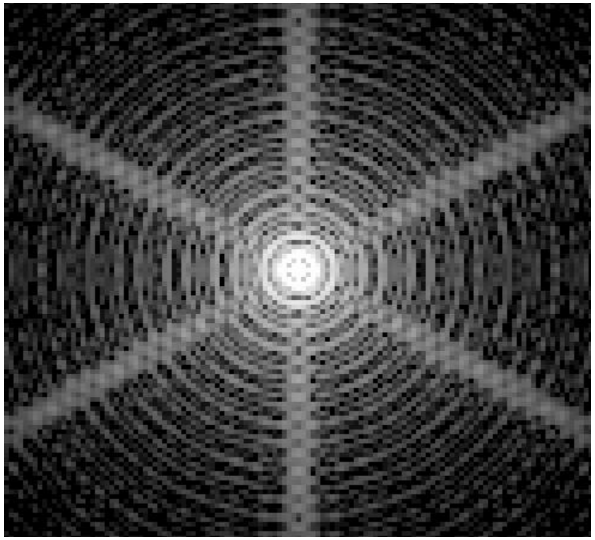


Two descriptions

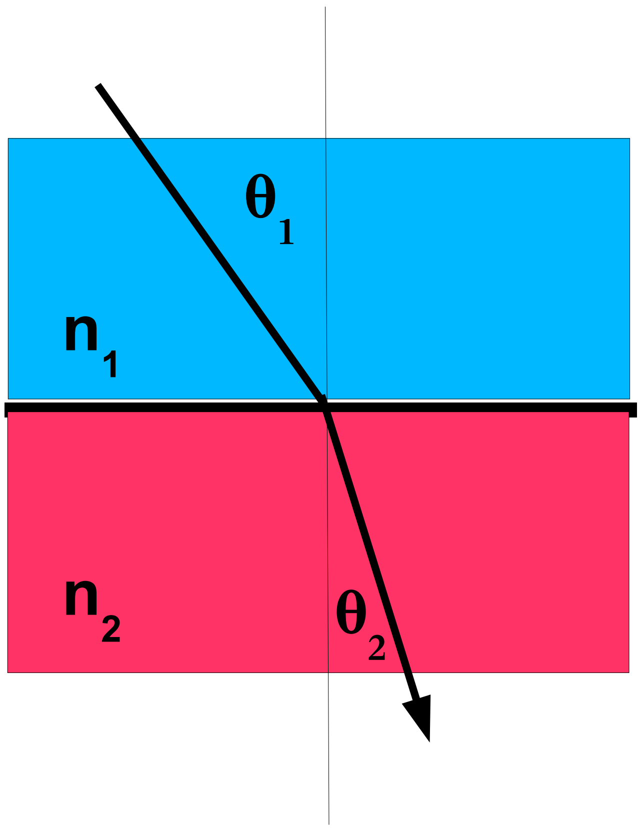
- **Geometric Optics**
  - **Ray Tracing**



- **Physical Optics**
  - **Diffraction (wave properties)**

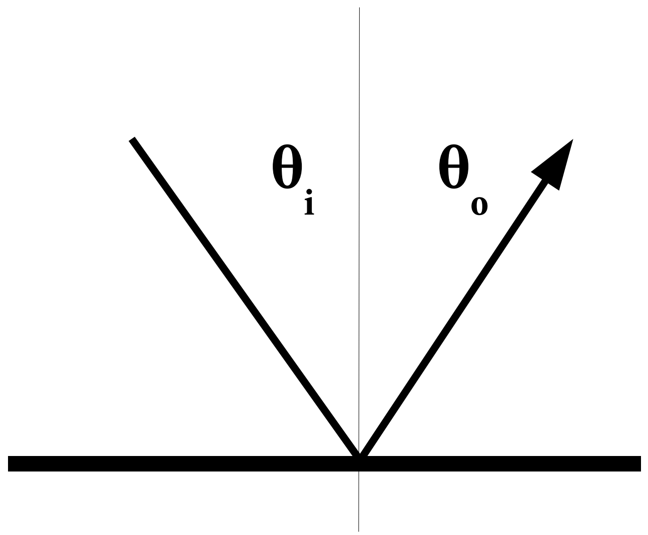


Fundamental Laws of Geometric Optics



$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

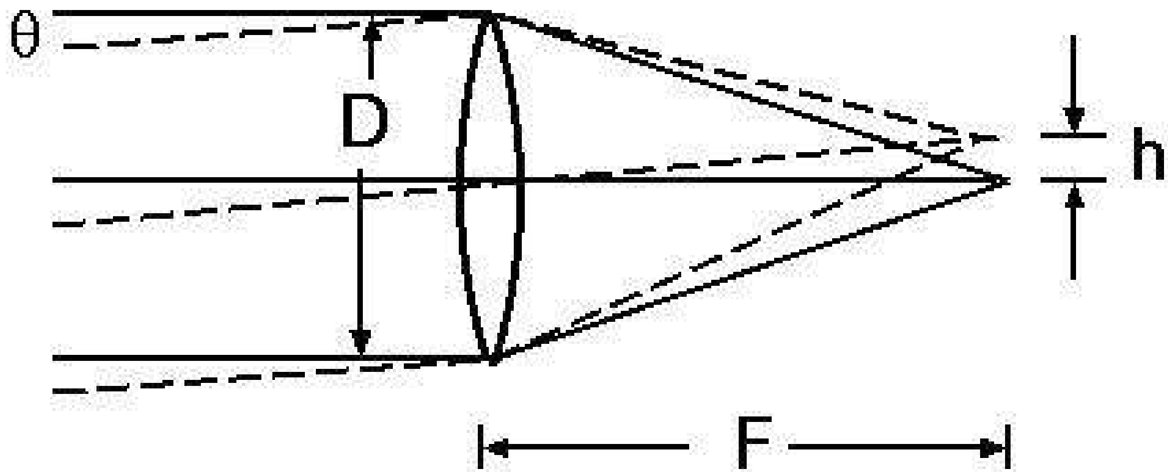
Snell's Law (Lenses)



$$\theta_i = \theta_o$$

Mirror

Simple Lens



$h = F\theta$

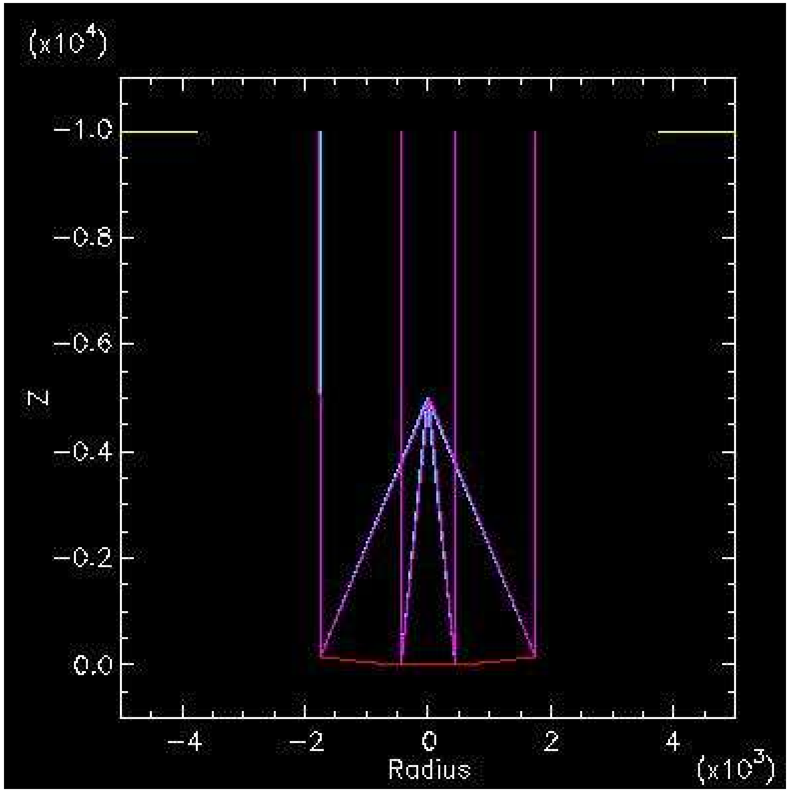
F = focal length

D = Lens diameter

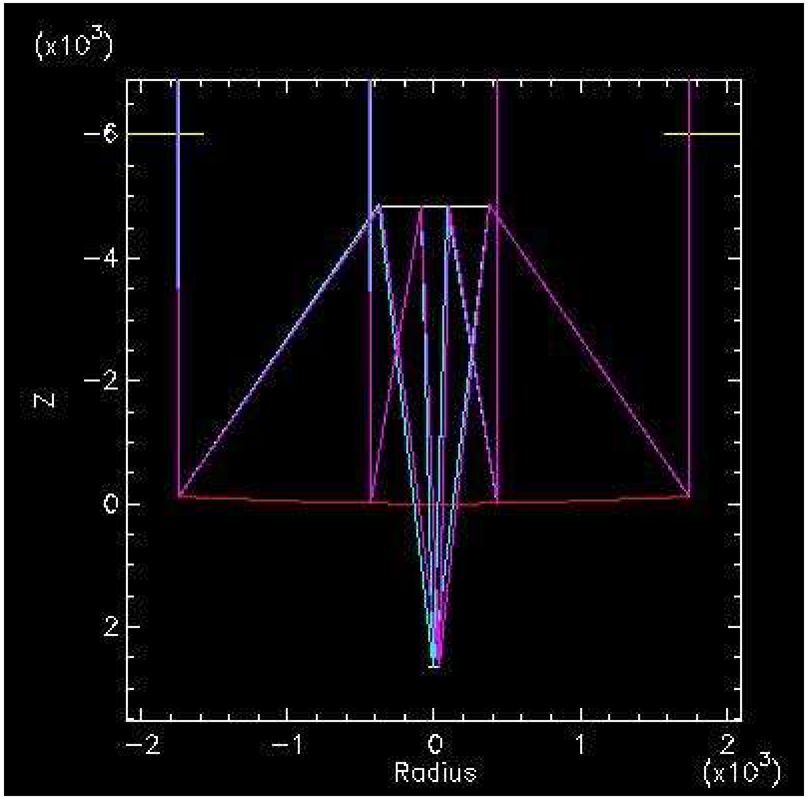
f = F/D = focal ratio

206265/F = scale (arcsec/mm)

Simple Designs



Newtonian (parabolic mirror)

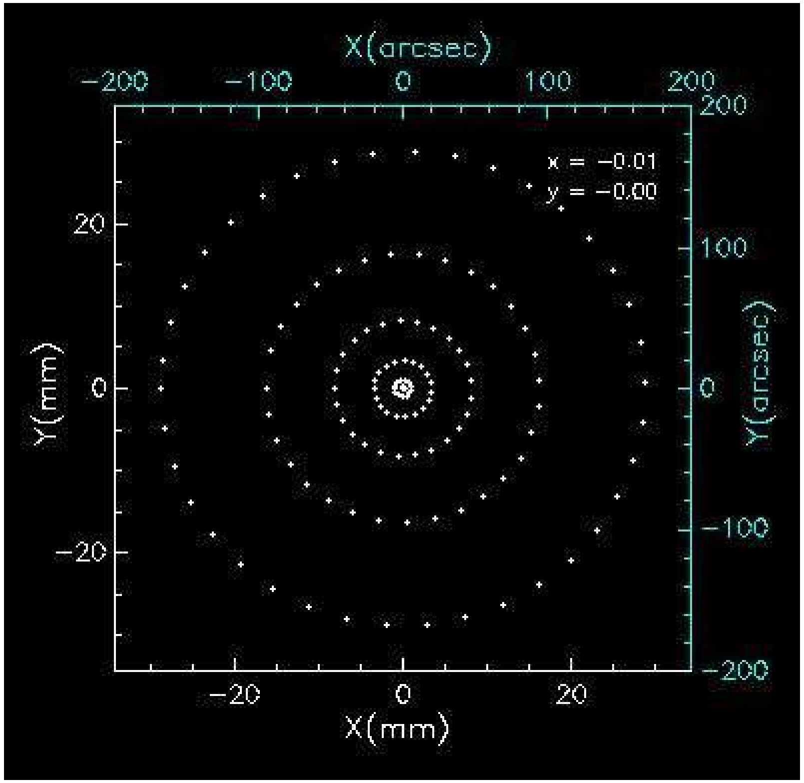


Cassegrain
(hyperbolic secondary)

Perfect images on-axis

Aberrations

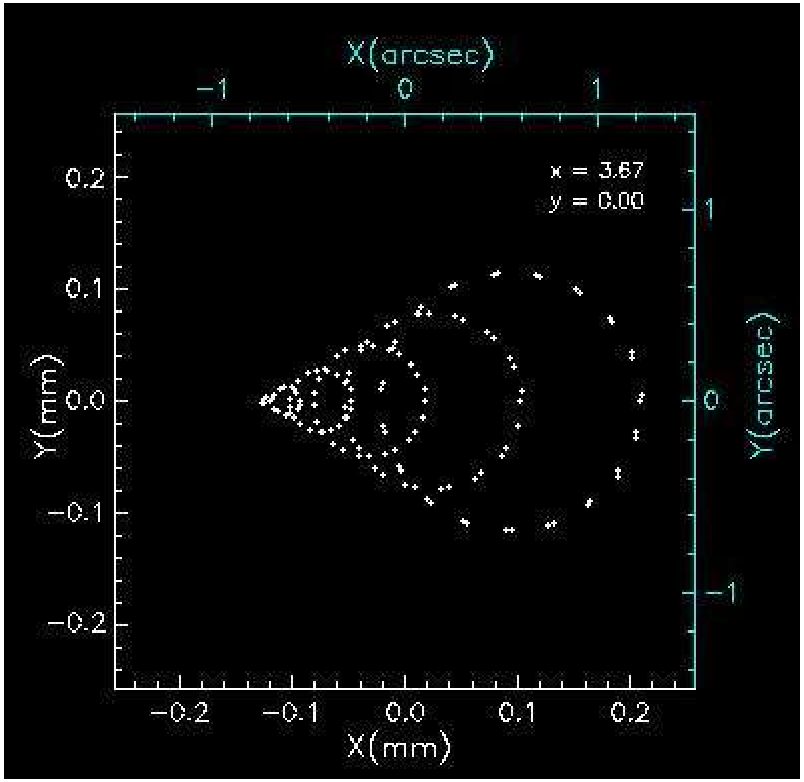
- **Spherical**
  - On-axis
  - Symptom: Light from edge of mirror has different focus from center
  - Cause: Spherical mirror or lens
  - Best focus - circle of least confusion
  - Cure: Parabolic Primary



Aberrations are reduced by adjusting surface shapes, element spacings, other free parameters in a design.

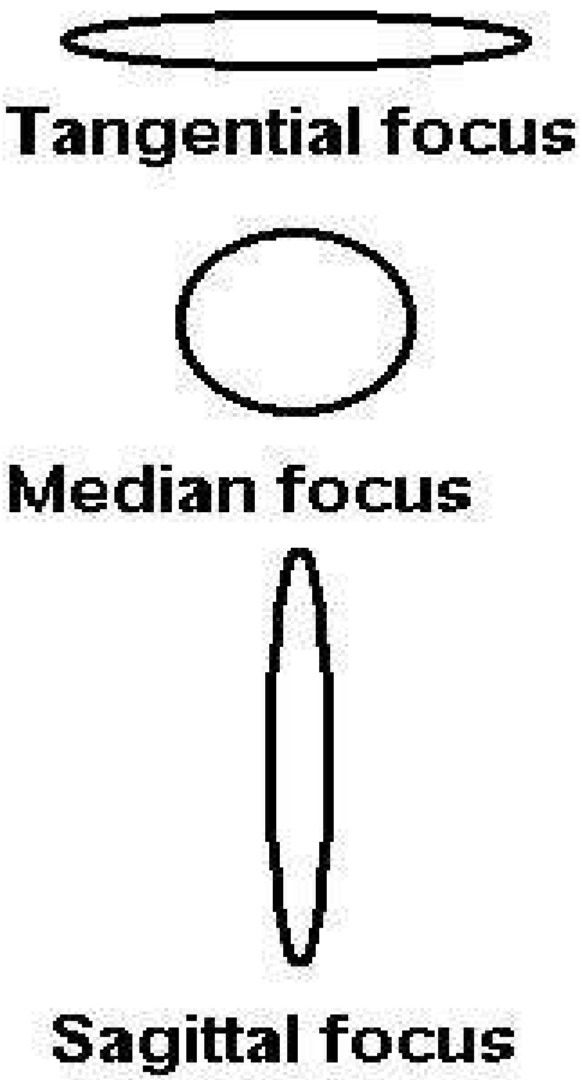
Aberrations

- Coma
  - Off-axis, limits useful field of view
  - Symptom: Light from edge of mirror has offset focus from center
  - Cause: Parabolic Primary
  - Cure: Hyperbolic Primary & Secondary mirror (Ritchey-Chretien)



Aberrations

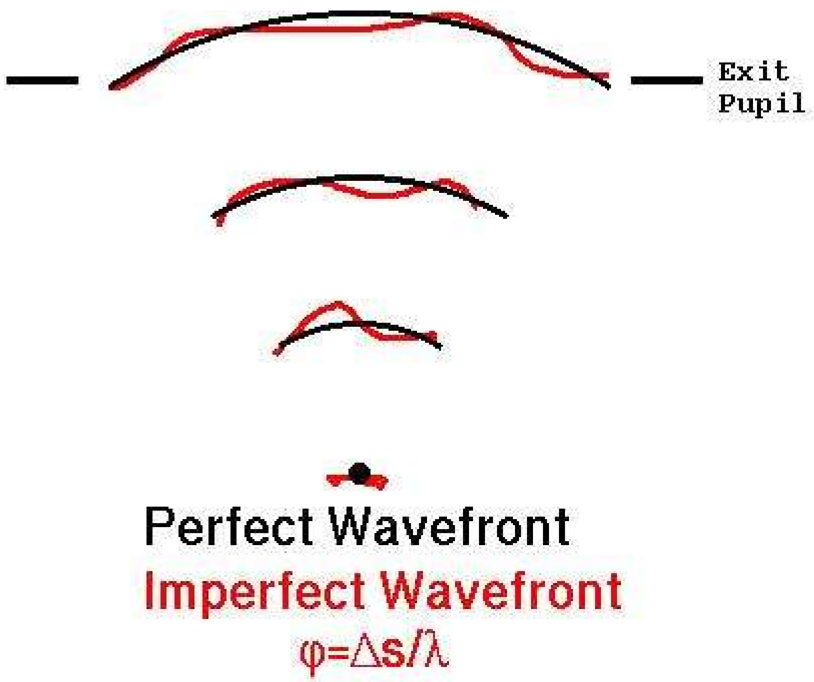
- **Astigmatism**
  - Off-axis, limits useful field of view
  - Symptom: Light from top, bottom of mirror have offset focus from left, right
  - Cause: Potato-chip shaped surface
  - Cure: Corrector lens or extra mirror



Additional Aberrations

- Distortion
  - Can't map a sphere onto a plane
- Field Curvature
- Longitudinal Chromatic Aberration (lenses only)
- Lateral Chromatic Aberration (lenses only)

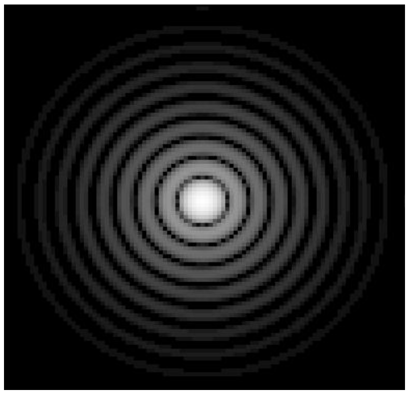
Fundamental of Physical Optics



Exit pupil is image of primary mirror as seen at the focal plane.

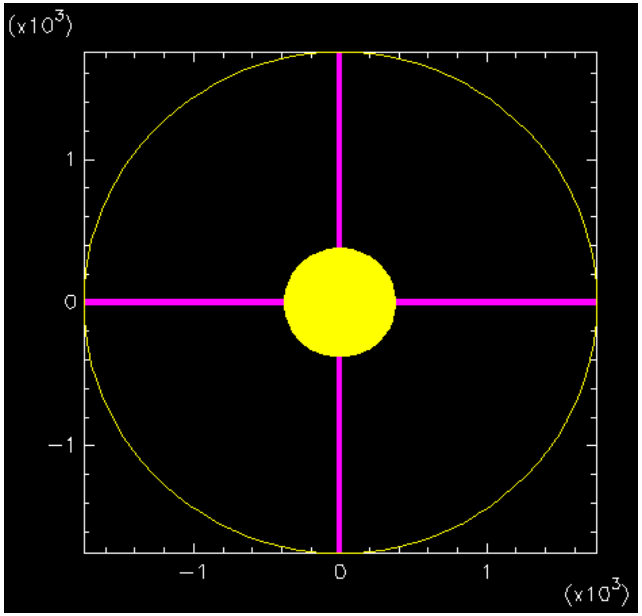
Image intensity at focal plane is Fourier transform of wavefront error ϕ integrated over exit pupil.

Perfect exit pupil ($\phi=0$):
Intensity = $J_1(v)/v$ where $v=\pi r/(f\lambda)$

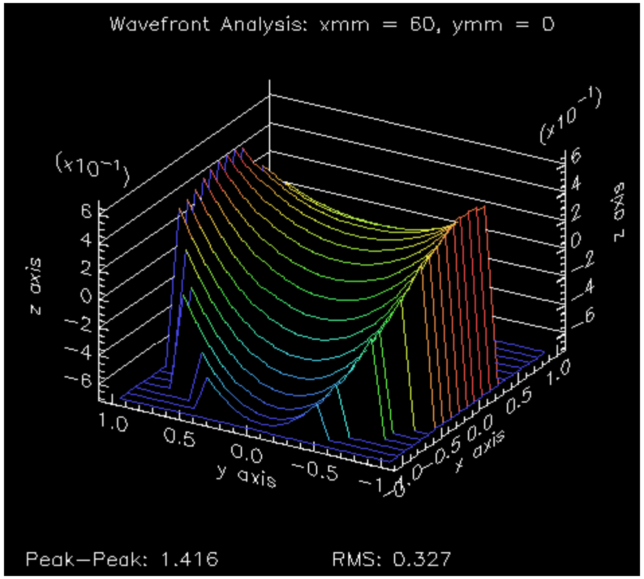


Airy disk: 1st dark ring at $r=1.22\lambda/D$
SNAP: 0.063" for B filter

4-M Diffraction



Exit Pupil



Wavefront error: r = 283 mm

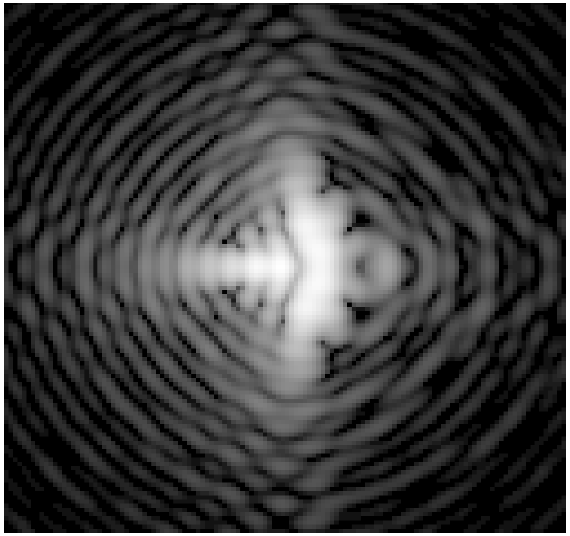


Image (closeup)

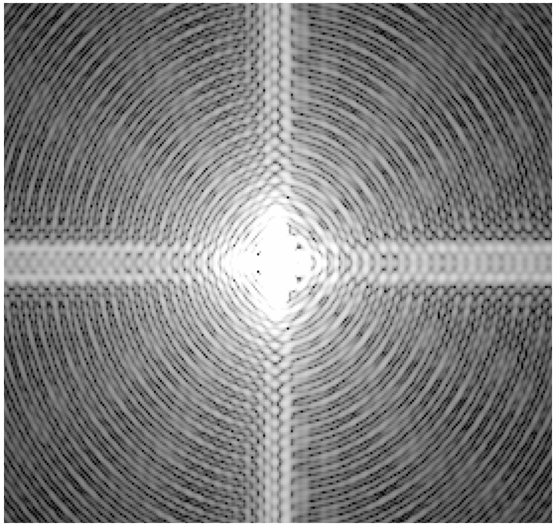


Image (wide field)

PSF (Point Spread Function) factors

- **Optical Design (aberrations and diffraction)**
- **Fabrication errors**
- **Surface roughness**
- **Optics cleanliness**
- **Collimation**
- **Atmospheric seeing (ground only)**
- **Filter characteristics (ghosting)**
- **Detector characteristics**

Optical Design Software

- **Windows**
  - **Zemax**
  - **Oslo (Free, useful version available!)**
  - **Code V**
- **Linux/Unix**
  - **trace (snap.fnal.gov => calibrations)**

DES Telescope Designs

Blanco 4-M Features:

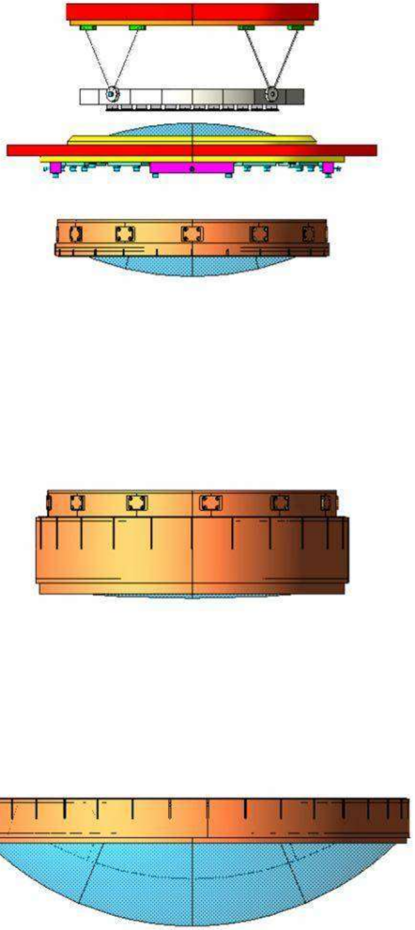
1. 4-M primary mirror f/2.7
2. "RC"
   Secondary mirror.
   Ritchie Cretien design - corrects both spherical aberration and coma over field ~40' diameter
   a) Hyperbolic primary
   b) Hyperbolic secondary
   c) f/8
2. Prime focus - multi-element corrector plus Mosaic CCD camera.

DECam Features:

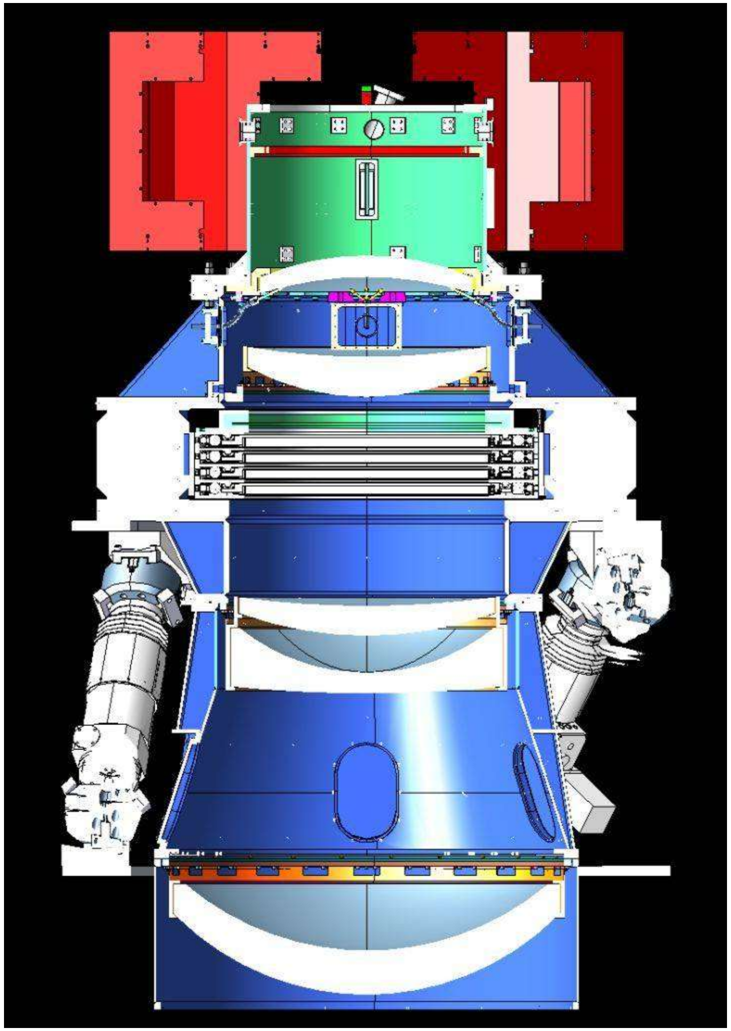
1. 5-element prime focus corrector
   All fused silica
   2 aspheric surfaces
2. Focal Length 10,000 mm
   Focal ratio f/2.9
   Scale 17.6arcsec/mm
   FOV 2.2 degrees (450 mm) diam
3. Flat focal plane
4. Optimized for filter bandpasses *g,r,i,z*
5. NOT INCLUDED:
   Atmospheric Dispersion Compensator

Optics and Mounting

C1 Precision Metrology

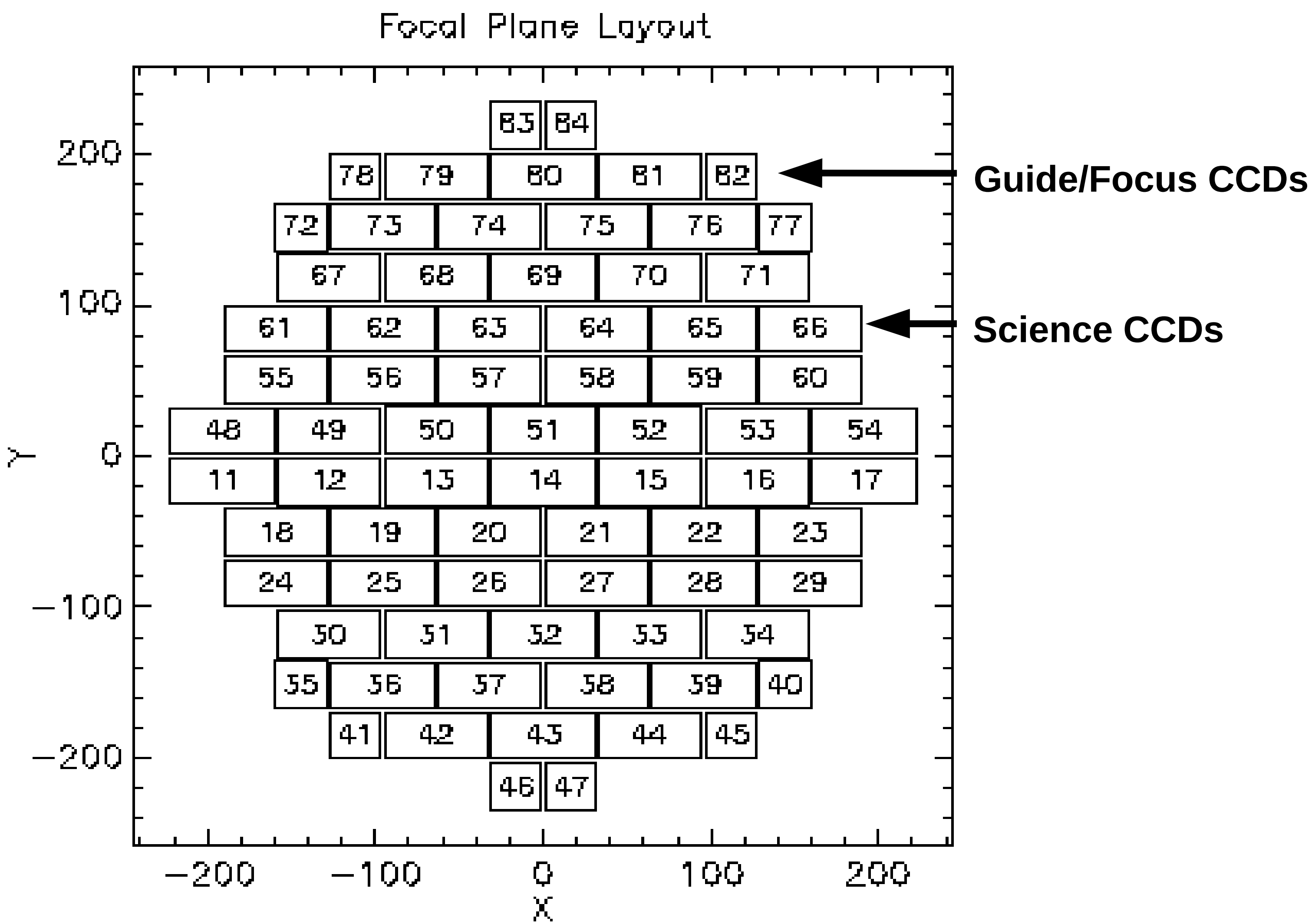


Corrector



Barrel with Hexapods

DECam 4-M Focal Plane



DES Optical Design: PSF error budget WL implications

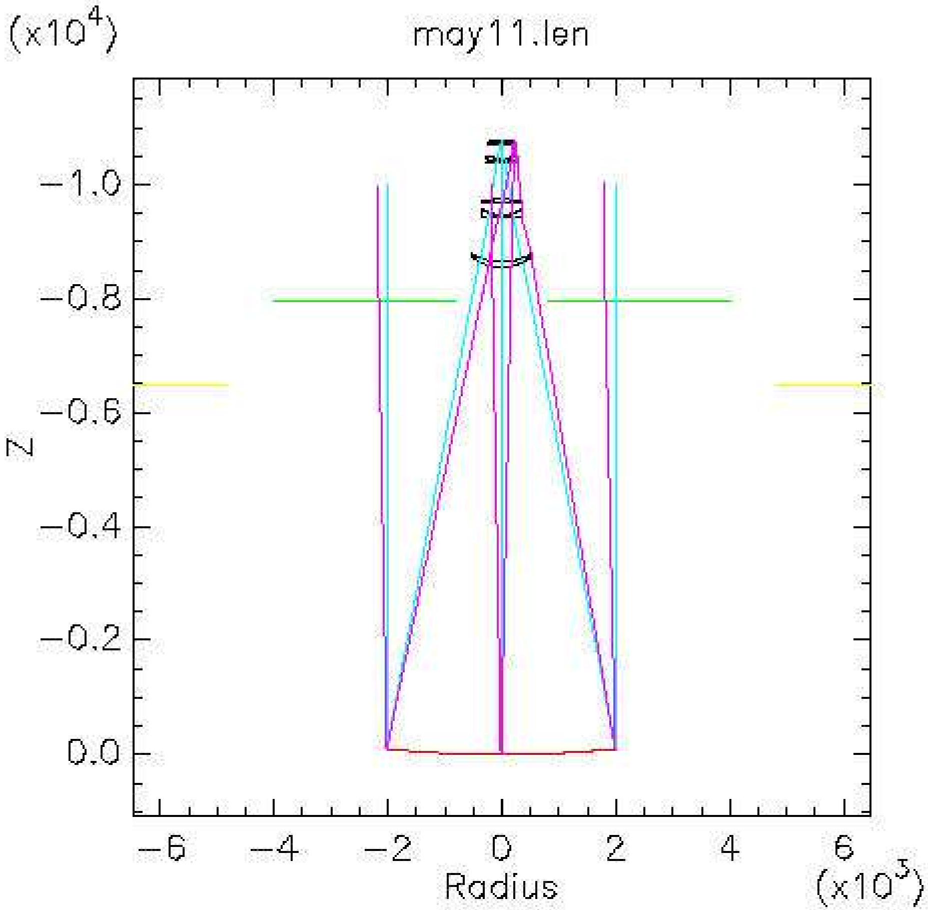
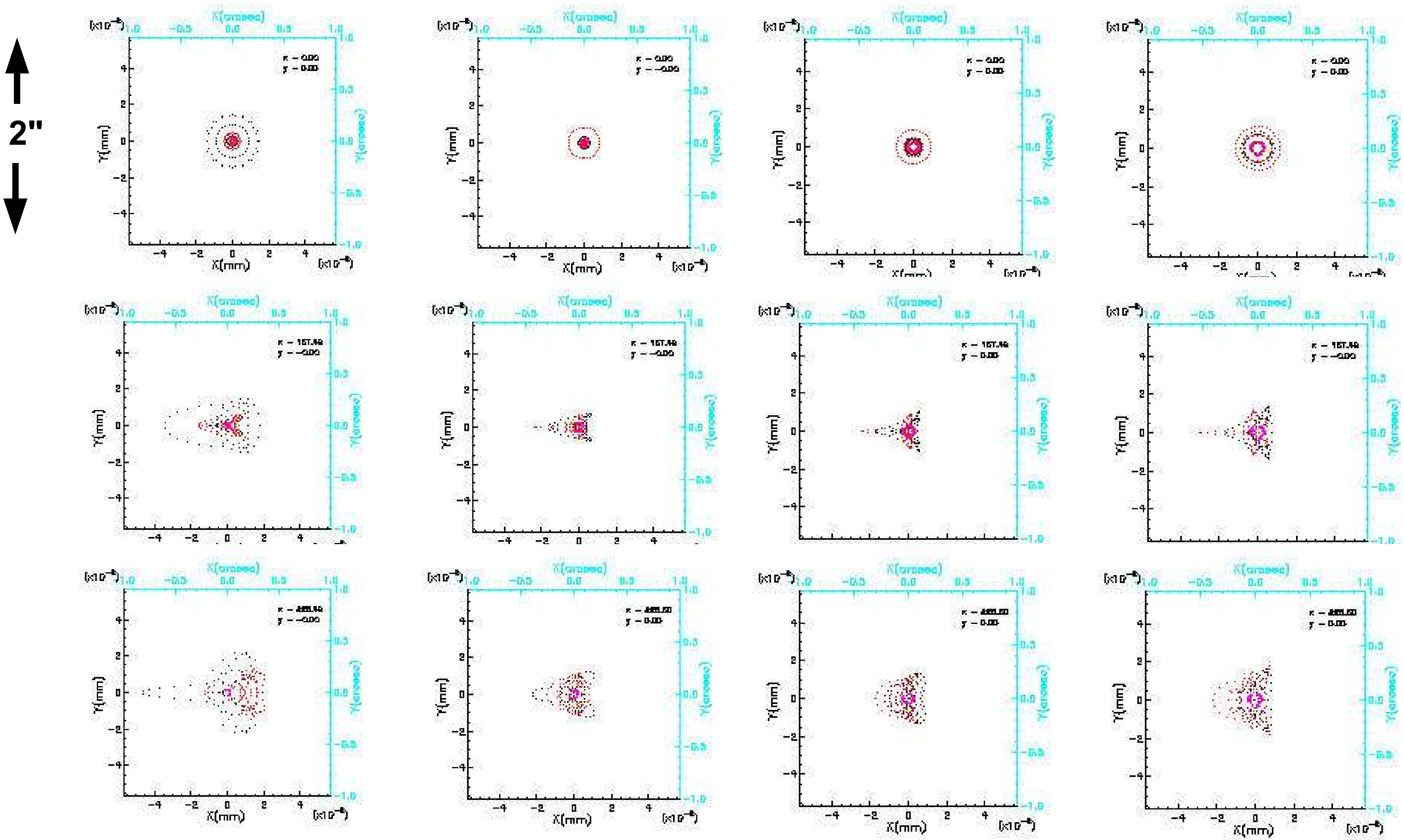


Image Quality Error Budget

Source		FHWM (1-d) (arcsec)	
Dome Seeing			Absorb in "contingency"
Telescope Guiding errors		0.03	WAG - take the same as focus errors.
Wind Shake		0	Assume "calm" night
Corrector			
	Design	0.27	Average of r, i (Blanco-2605)
	Manufacturing tolerances	0.11	(Radii, index, thickness, polish)
	Glass homogeneity	0.04	Striae, etc 2.e-6
	Assembly errors	0.08	(decenter, tilt)
	Flexure	0.04	Stability under gravity loading
	CCD Focal Plane flatness	0.05	Peak-peak 30 micron z error.
	Lens Deformation	0.03	Gravity loading
	Thermal performance	0.06	Worst-case change of 30C (Steel)
CCD Diffusion		0.31	From LBNL tests - expected performance (7.5 microns 1-D)
Depth-of-focus in CCD		0.03	From Kubik report (i' depth of focus only)
Primary Mirror figure		0.16	From CTIO mirror testing report
Primary mirror support (static)			Absorb in "contingency"
Primary mirror support flexure			Assume "active optics" are perfect
Telescope Collimation (static)		0.05	200 micron offset of primary mirror
Telescope flexure/mirror translation			Absorb in Contingency
Focus		0.03	Scaled from 2.5 m performance
TOTAL (Tel+Instrument)		0.48	
Contingency		0.27	Primary mirror support, dome seeing, ...
Requirement		0.55	

PSF v. Field Angle, Filter

g filter	r filter	i filter	z filter	Field Radius



Field Radius: 0 mm, 158 mm, 225 mm

Image Quality

(early design)

D80 vs. filter, field position

Field Radius (mm)	g	r	i	z
0	0.32"	0.11	0.17	0.31
45	0.35	0.19	0.21	0.34
90	0.39	0.14	0.22	0.33
135	0.40	0.21	0.25	0.33
180	0.50	0.32	0.36	0.42
226	0.59	0.37	0.41	0.47

DARK ENERGY Survey

Weak Lensing Equation

Apparent Image

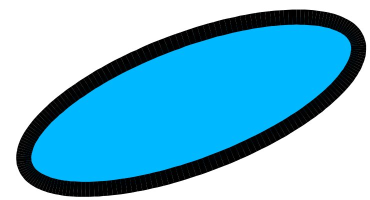
=

(

Instrinsic Image

x

Gravitational shear



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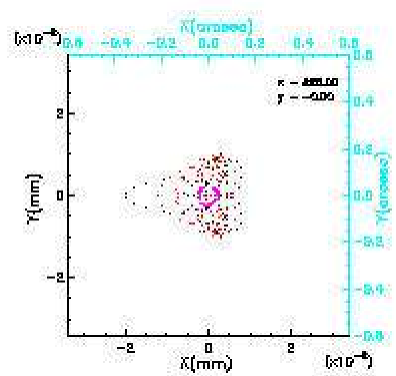
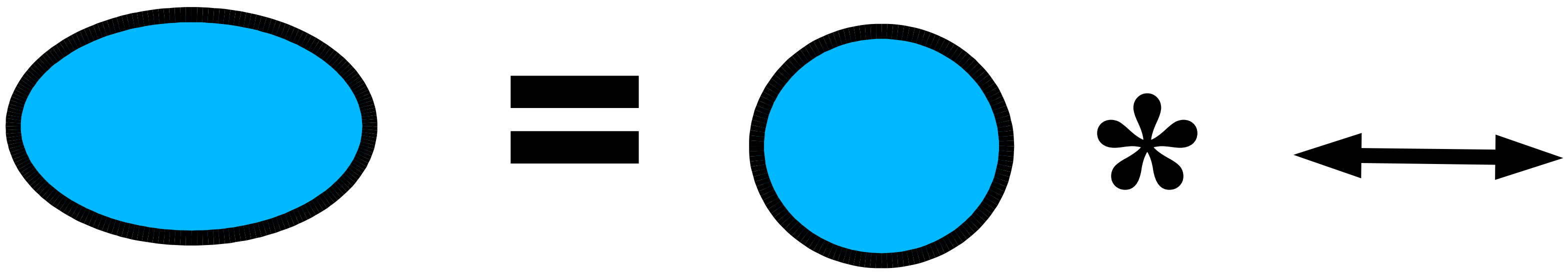


Point Spread Function

PSF is measured from bright stars near a sample galaxy

Model of a PSF



Elliptical PSF   Circular PSF   "Whisker"

Circular PSF has contributions from intrinsic PSF & seeing
Whisker PSF has contributions from intrinsic PSF & tracking errors.

I will use the amplitude of a "whisker" from the intrinsic PSF as my metric for weak lensing calibration, since this mimics the gravitational shear signal and is easy to calculate.

For convolution, FWHM's add in quadrature.

A 0.1% error in shear for 1.2" FWHM galaxies => 0.06" FHWM error in the equivalent PSF "whisker".

Metrics for weak lensing

- Shear signal: (1 - b/a) ~ 1%
- Require systematic errors to be "small" compared to statistical errors
  - Estimated statistical error from full DES experiment is 0.01% shear (1 sigma)
  - Estimated “cosmic variance” is also .01% shear (1 sigma)
  - Equivalent "whisker" for galaxy 0.9 arcsec FWHM is 0.014 arcsec
- We cannot make PSF this round. HOWEVER, the goal is to measure (i.e. calibrate) the PSF to this level.

PSF Shape Calibration

- **Calibrate PSF for each CCD and each telescope pointing independently.**
- **Each 2nd central moment ($<x^2>$, $<y^2>$, $<xy>$) fitted as a linear function of CCD row, CCD column.**
- **Compute r.m.s. residuals.**
- **Combine multiple telescope pointings using principal components analysis. R.M.S. residuals for 2nd moments are reducible by a factor 10 ==> whisker residuals reduced by 3x.**
- **==> Requirement: r.m.s. systematic error in whisker length calibration per frame < .04-.05 arcsec (after removing bilinear fit).**

PSF Performance

- Current Blanco corrector: σ_{rms} = 0.08 arcsec
- Current Mayall corrector σ_{rms} = 0.07 arcsec
- DES Blanco-2602-v203: σ_{rms} = 0.045 arcsec

Mathematically ...

Dilution Polarization

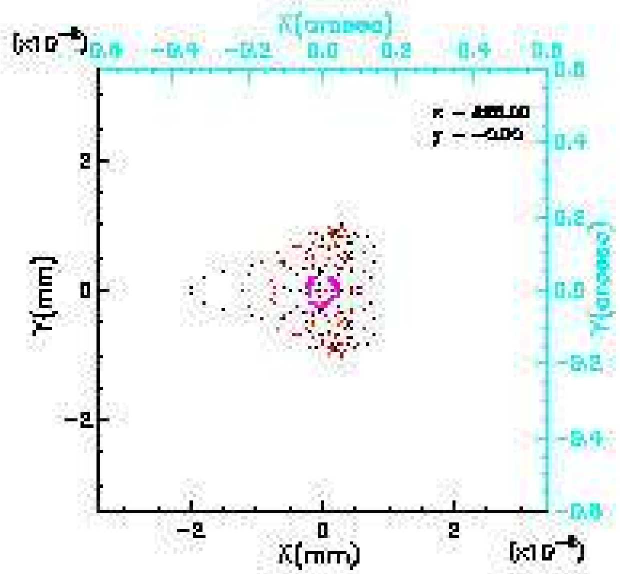
PSF = $\begin{bmatrix} \langle x'^2 \rangle & \langle x'y' \rangle \\ \langle x'y' \rangle & \langle y'^2 \rangle \end{bmatrix} = \begin{bmatrix} k & 0 \\ 0 & k \end{bmatrix} + \begin{bmatrix} w & \langle x'y' \rangle \\ \langle x'y' \rangle & -w \end{bmatrix}$

where $$k = (\langle x'^2 \rangle + \langle y'^2 \rangle)/2$$
$$w = (\langle x'^2 \rangle - \langle y'^2 \rangle)/2$$

Whisker length *c*: $$c^2 = \sqrt{(\langle x'^2 \rangle - \langle y'^2 \rangle)^2 + 4\langle x'y' \rangle^2}$$

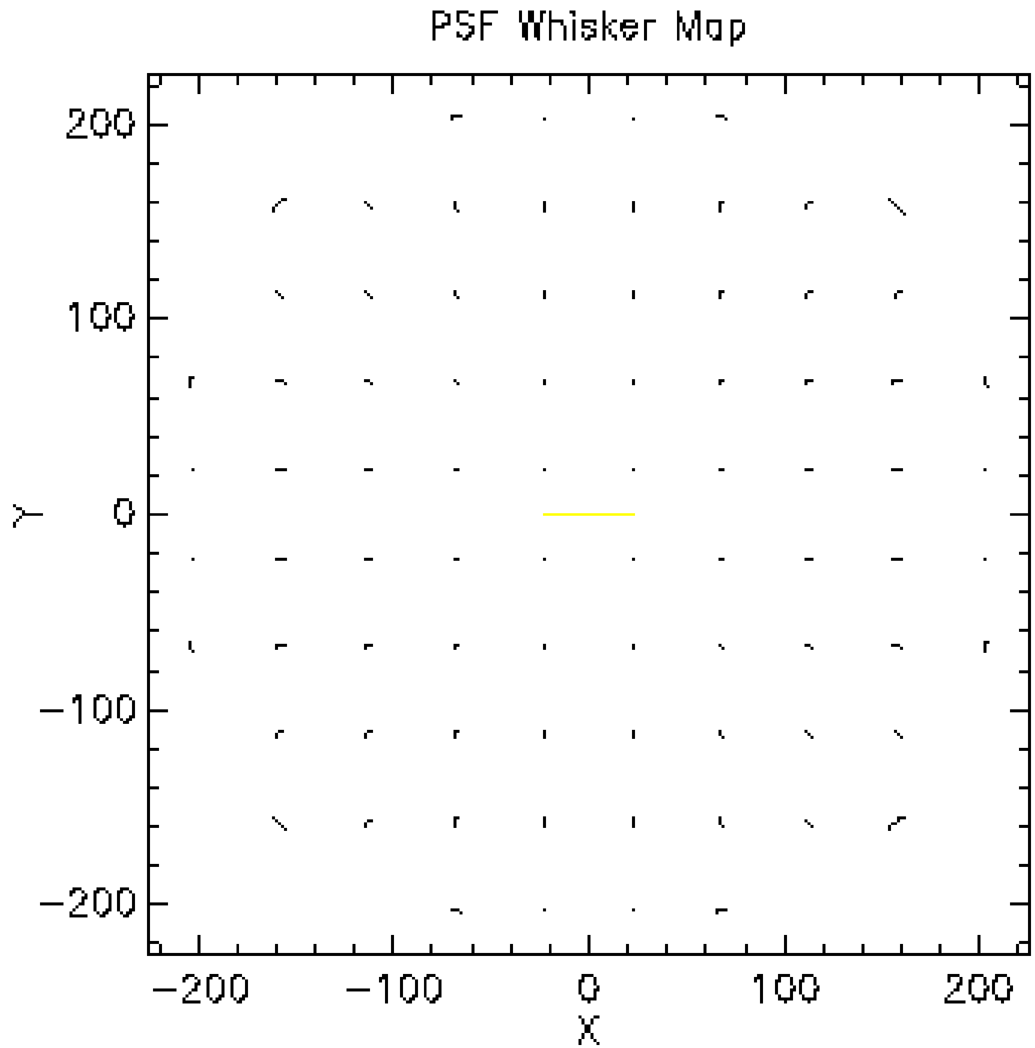
PSF = PSF$_{\text{seeing}}$ + PSF$_{\text{tracking}}$ + PSF$_{\text{optics}}$ + ...

Example



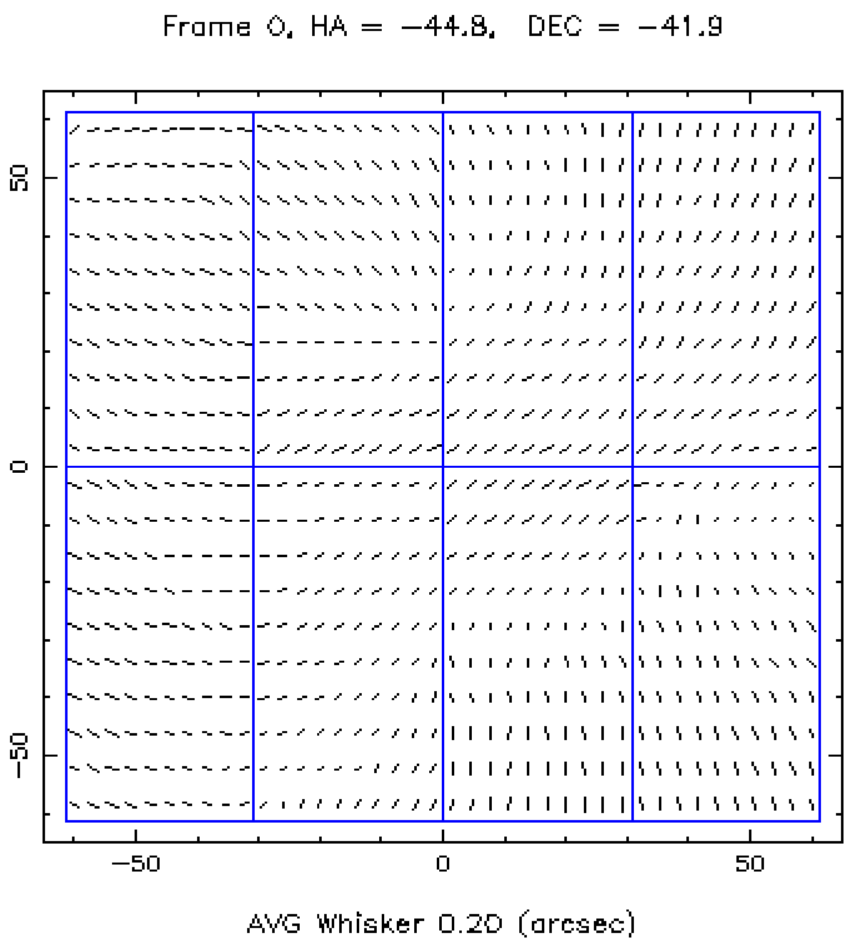
Design: may11
Location: Edge of field (225 mm radius)
Filter: r' (0.56 and 0.69 microns)
FWHM: 0.2"
Whisker length: 0.1"
Whisker orientation: 90°

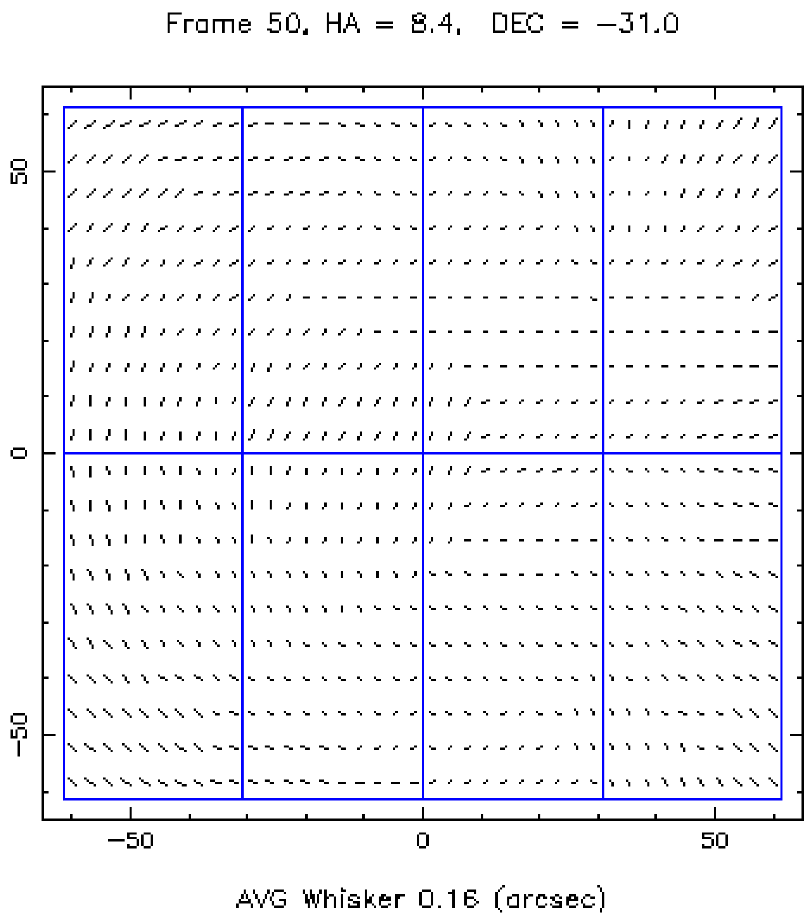
Static whisker map (*i* band) due to optics



Maximum whisker: 0.2 arcsec

Mosaic II Sample Data





rms whisker lens is 0.2 arcsec after subtracting constant PSF

Physical factors affecting static psf

- Intrinsic design
- Fabrication errors (lens radii, refractive index variations,etc)
- Corrector assembly errors (tilt, position errors, etc)
- Telescope collimation (primary mirror centering, tilt, etc.)
- Detector assembly errors (nonflat focal plane, detector position w.r.t corrector)

Physical factors causing dynamic PSF

- Thermal
  - Focus
  - Mirror distortion (astigmatism)
- Gravity
  - Mechanical motions (coma, astigmatism)
- Atmosphere
  - Seeing (image size; spatial changes?)
  - Differential Refraction (rotating ADCs?)
- Earth rotation
  - Tracking & guiding errors

STATIC: Whisker length variation across focal plane (3' spacing)

Filt	zen	Blanco-602	
		Mean	diff
g	0	0.17	0.11
r	0	0.13	0.07
i	0	0.11	0.08
z	0	0.05	0.10

DYNAMIC: Whisker length vs. differential refraction

Filter	zenith angle	may11 Mean	diff
g	0	0.28	0.00
g	35	0.39	0.44
g	55	0.82	0.85
r	0	0.15	0.00
r	35	0.19	0.17
r	55	0.36	0.35
i	0	0.23	0.00
i	35	0.24	0.09
i	55	0.26	0.20
z	0	0.27	0.00
z	35	0.27	0.05
z	55	0.28	0.11

DYNAMIC: Focus

- Focus loop servo corrects for changes in focus ==> servo "error". What is impact on weak lensing?
- SDSS 2.5 telescope focus loop ==> peak servo error is 0.1 arcsec image blur for "good seeing".
- Equivalent Blanco defocus is 16 microns => whisker length of .1 arcsec (i band).
- Note that this is peak; rms is smaller.

DYNAMIC: Decollimation

- Proposed requirement of maximum 200 micron decollimation between primary mirror and corrector
- This decenter introduces a whisker length of 0.11 arcsec

DYNAMIC: Temperature variations

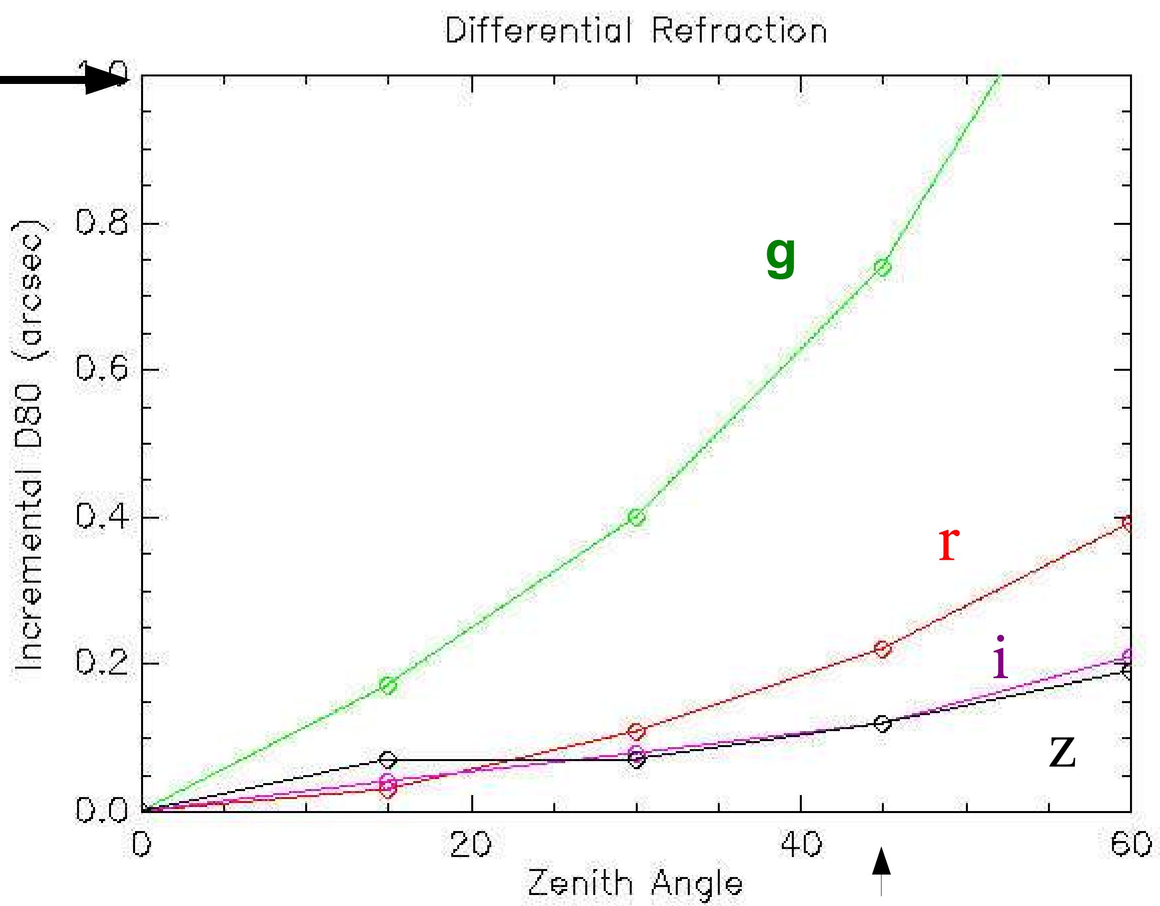
- Change telescope size, lens shapes, refractive indices by 30 C.
- Refocus
- Whisker length changes by .17 arcsec.

DYNAMIC: Primary Mirror Aberrations

- Spherical Aberration
  - 1.7 microns
  - Not important
- Coma
  - Degenerate with decollimation/tilt errors
- Astigmatism
  - .6 microns
  - Important if focus not controlled
- Trefoil
  - .04 microns
  - Probably not important
- Quadrafoil
  - .18 microns
  - Probably not important

Impact of no ADC

1 arcsec FWHM

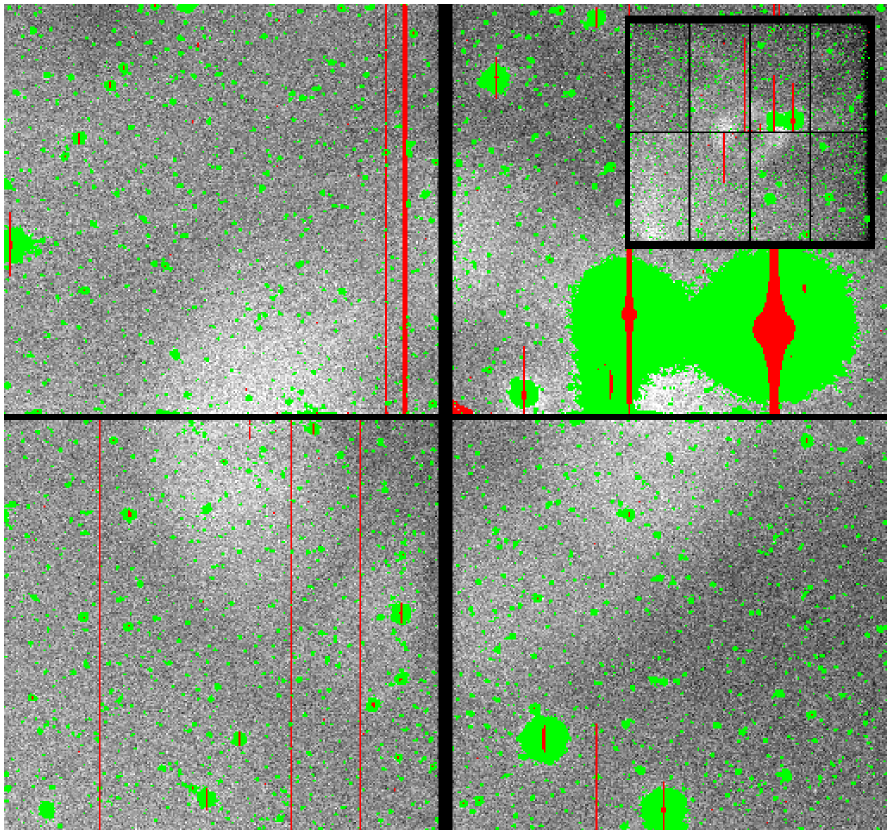


Survey limit; LMC, SMC limits

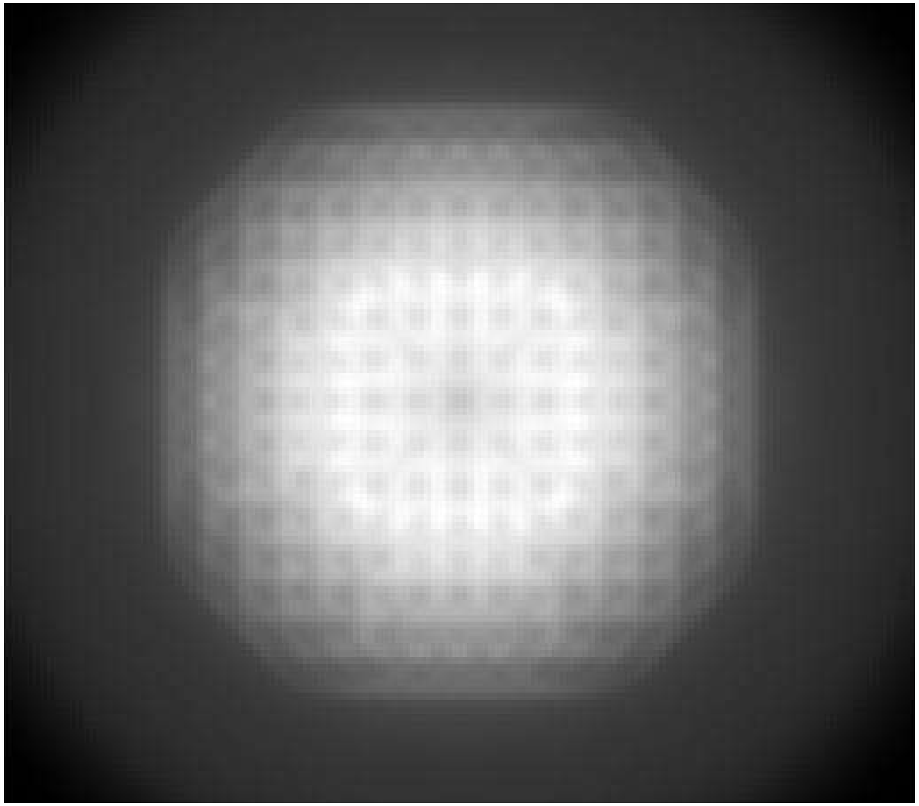
Photometric Calib & Ghosting

- Calibration - convert ADU to CGS
- Flatfielding used to correct for pixel-pixel sensitivity variations across focal plane.
  - Illuminate telescope with a dome flatfield screen
  - OR median average many science frames.
  - ASSUME illumination or sky brightness is constant - any variation measures sensitivity
- HOWEVER CCDs are “shiny” - CCD - corrector reflections are non-negligible

Ghosting



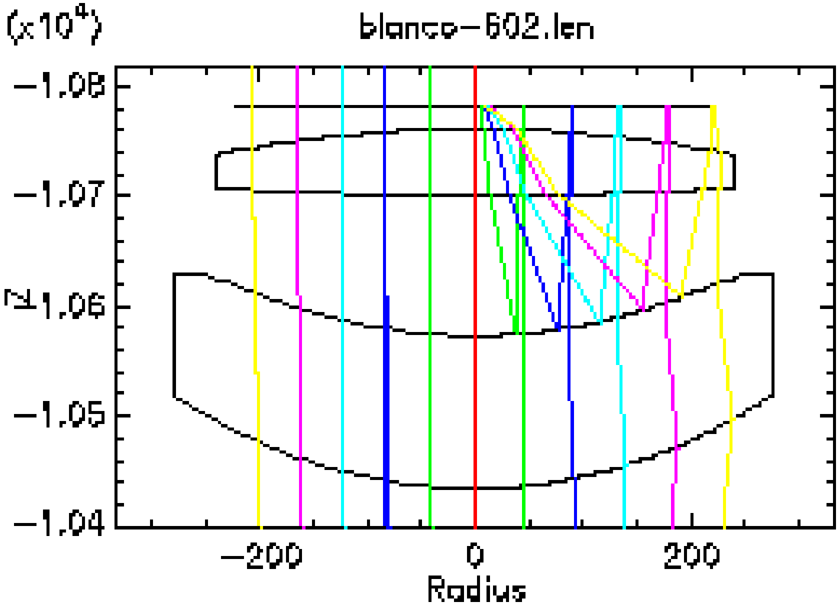
Mayall 4 m Mosaic I image



DECamPrediction from design

Exit Pupil Ghosting

Exit Pupil Ghosting - detail



Ghosting Requirements

- Exit Pupil: Gradient across length of 1 CCD no more than 3%.
  - Assumes 15% CCD reflection, 1.6% lens surface reflection
  - Induced photometric error (if uncorrected) is 0.9% for a single frame.
  - Current design: max gradient is 2.5%
- Bright star: 6th mag star produces ghost no brighter than 25th mag/sq. arcsec
  - Main impact is spacing of window from focal plane.

Optics - Current Status

- Lenses C3, C5 completed by SESO and delivered
- Lens C2 completed but awaiting final inspection.
- Lens C4 has just been declared “good enough” (difficult aspheric surface)
- Lens C1 in progress (December?)
- Mounting in cells and barrel will take ~5 months