LSST Integrated Model with Phosim

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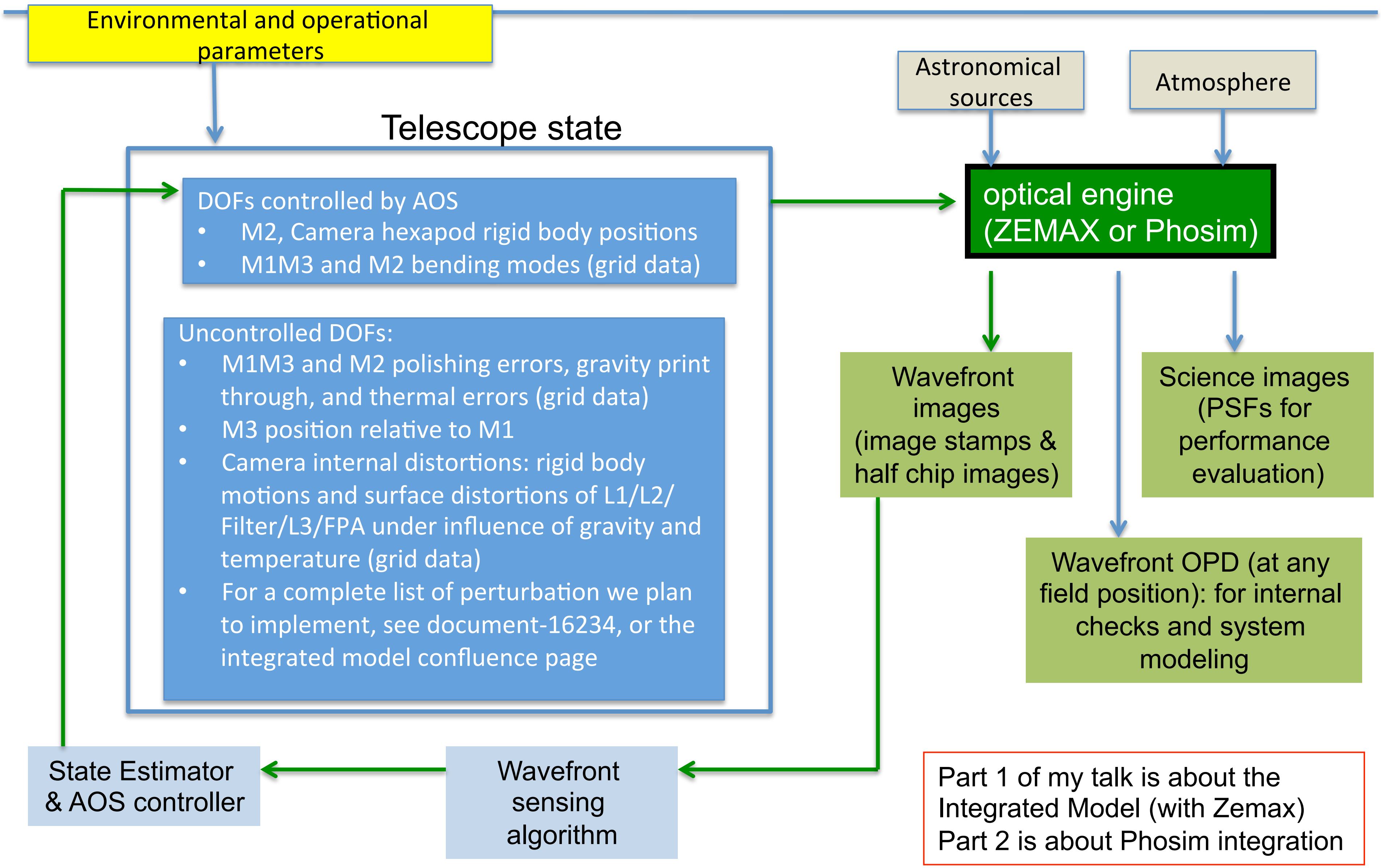
LSST Integrated Model

- The LSST Integrated Model is a high-fidelity model of the to-be-built observatory.
- The model is integrated because it is a joint simulation of optics, structure and control.
- It links the engineering parameters and the environmental and operational parameters to two key LSST performance metrics: image quality/size and ellipticity.
- What do we need it for
  - evaluate system performance against requirements
  - predict the observatory's scientific performance
  - interpret system test results
  - support trade studies during construction.
  - Simulate commissioning activities

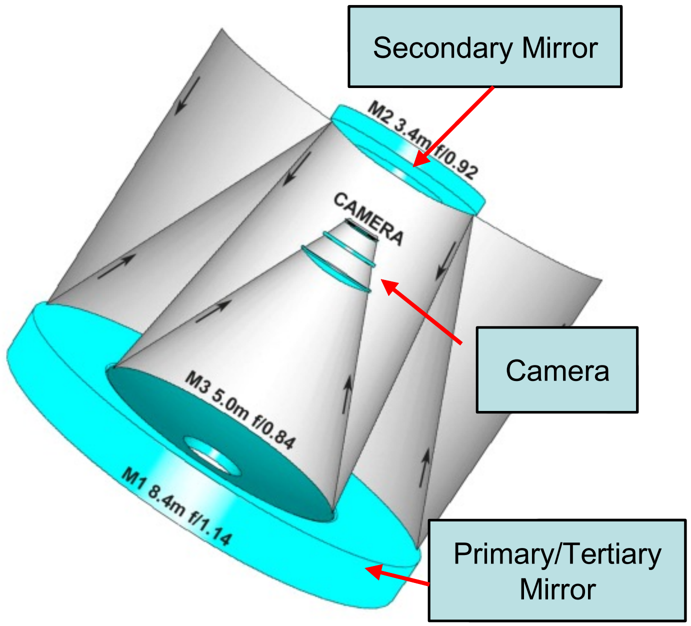
The More Technical Simulation Architecture



The Matlab + Zemax Simulation Framework

- We built an Integrated Model of LSST under the Matlab+Zemax framework during 2013-2014.
- So far, the model has been used for
  - Wavefront sensing algorithm testing (Appl. Opt. 54, 9045-9054 (2015))
  - Simulation and optimization of AOS control (Proc. of SPIE Vol. 9150 91500H (2014))
  - M1M3 optical performance evaluation/incl. crows' feet (document-17171)
  - M1M3 actuator force accuracy requirement study (document-20263)
  - Impact of sensor height variation on PSF ellipticity (document-20264)
  - Impact of L1 refraction index inhomogeneity on image quality (need to track down final documentation with Brian Bauman)
  - Analysis of LSST dome seeing (document-18023) (didn't involve the optical engine – Zemax, in this case)
  - TMA dynamic/control damping (document in progress)
- The AOS simulations involve most of the parts in and around the optical engine (Zemax before, Phosim now)
- I will use the AOS as the example to demonstrate how the model works

System Perturbations: What's in the Current Model



DOFs controlled by AOS

- M2 hexapod rigid body positions (5)
- Camera hexapod rigid body positions (5)
- M1M3 bending modes (20)
- M2 bending modes (20)

Green: has been implemented

An Incomplete list of Uncontrolled DOFs:

- M1M3:
  - M1M3 polishing errors
  - gravity print through
  - thermal induced errors
  - M3 position relative to M1
- M2:
  - polishing errors
  - gravity print through
  - thermal induced errors
- Camera internal distortions:
  - rigid body motions of L1/L2/Filter/L3/FPA (gravitational & thermal)
  - surface distortions of L1/L2/L3 (gravitational & thermal)
  - Lens polishing errors
  - Lens and filter Installation errors
  - Detector installation errors

System Image Quality Budget

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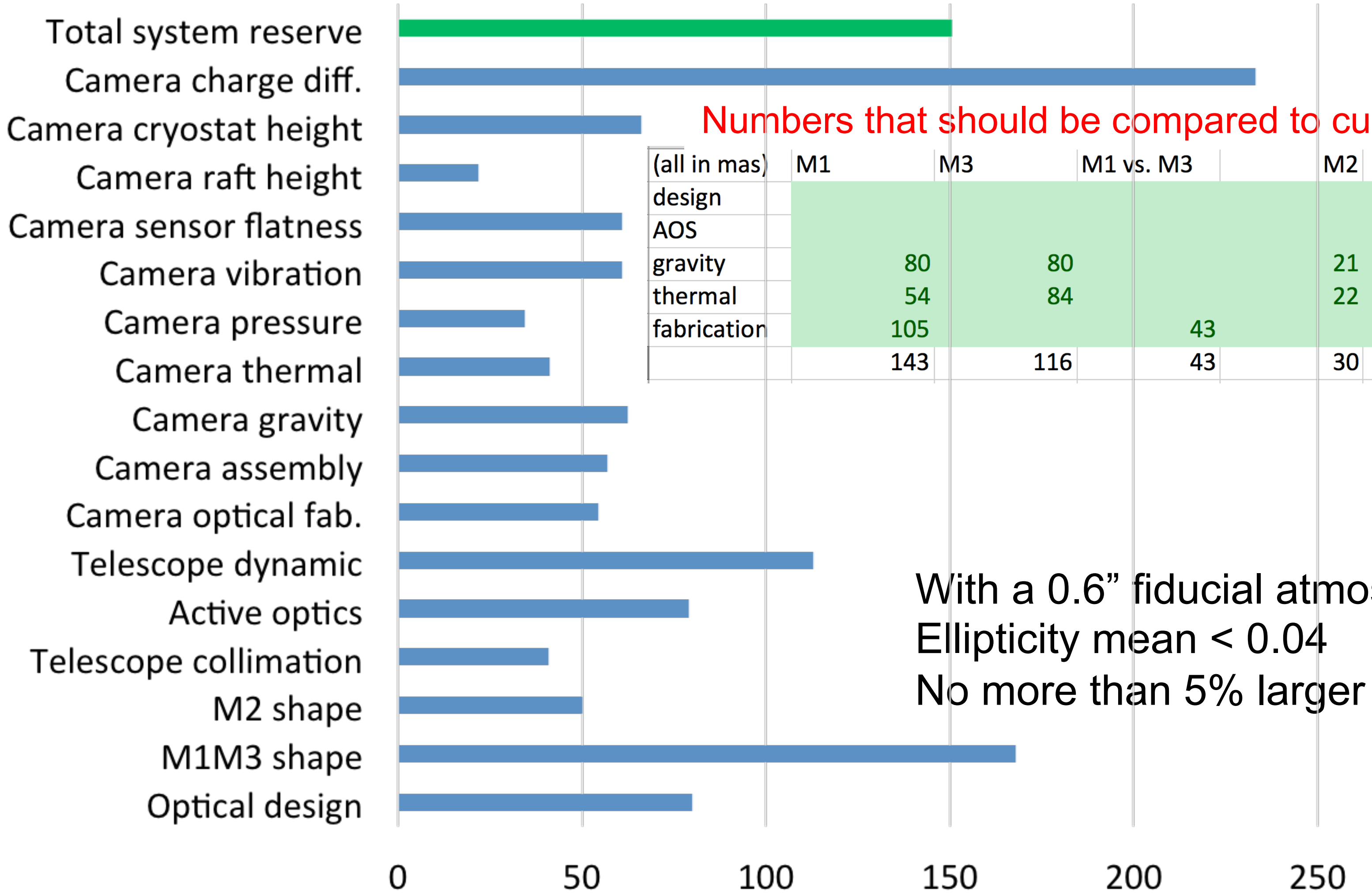


Numbers that should be compared to current simulations

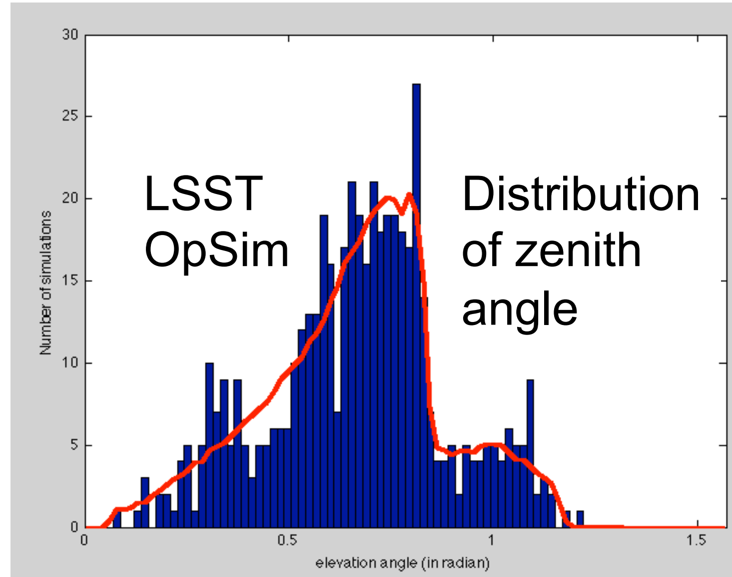
(all in mas)	M1	M3	M1 vs. M3	M2	Camera	total
design						80
AOS						79
gravity	80	80		21	63	131
thermal	54	84		22	28	106
fabrication	105		43			113
	143	116	43	30	69	232

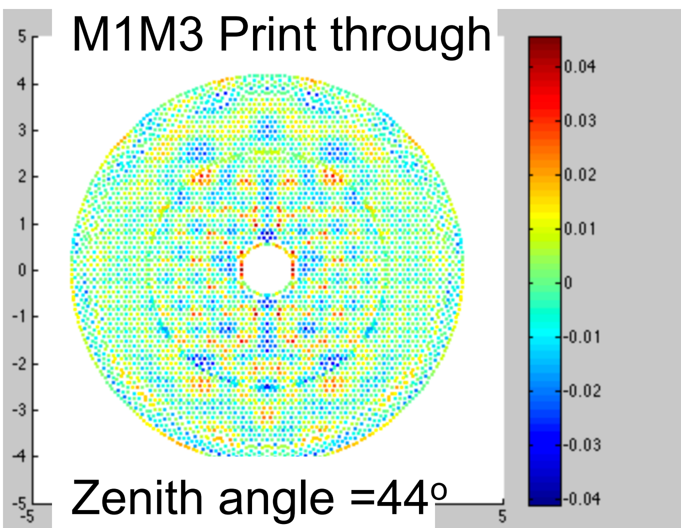
With a 0.6” fiducial atmosphere,
Ellipticity mean < 0.04
No more than 5% larger than 0.07

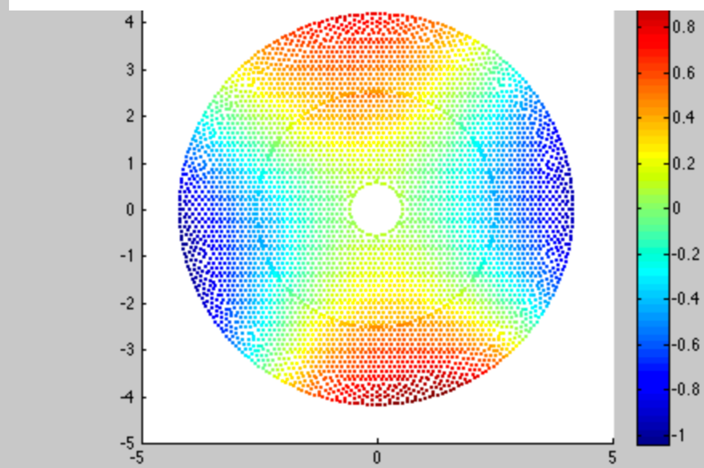
(Effective FWHM In mas)

M1M3 Gravitational Print Through

- Zenith angle is drawn randomly from distribution provided by LSST Operation Simulator.
- For any given zenith angle the actuator forces are optimized for achieving the optimal mirror surface shape.
- As a very conservative estimate, we add 5% noise on the actuator forces for imperfect repeatability.







M1M3 Thermal Induced Errors

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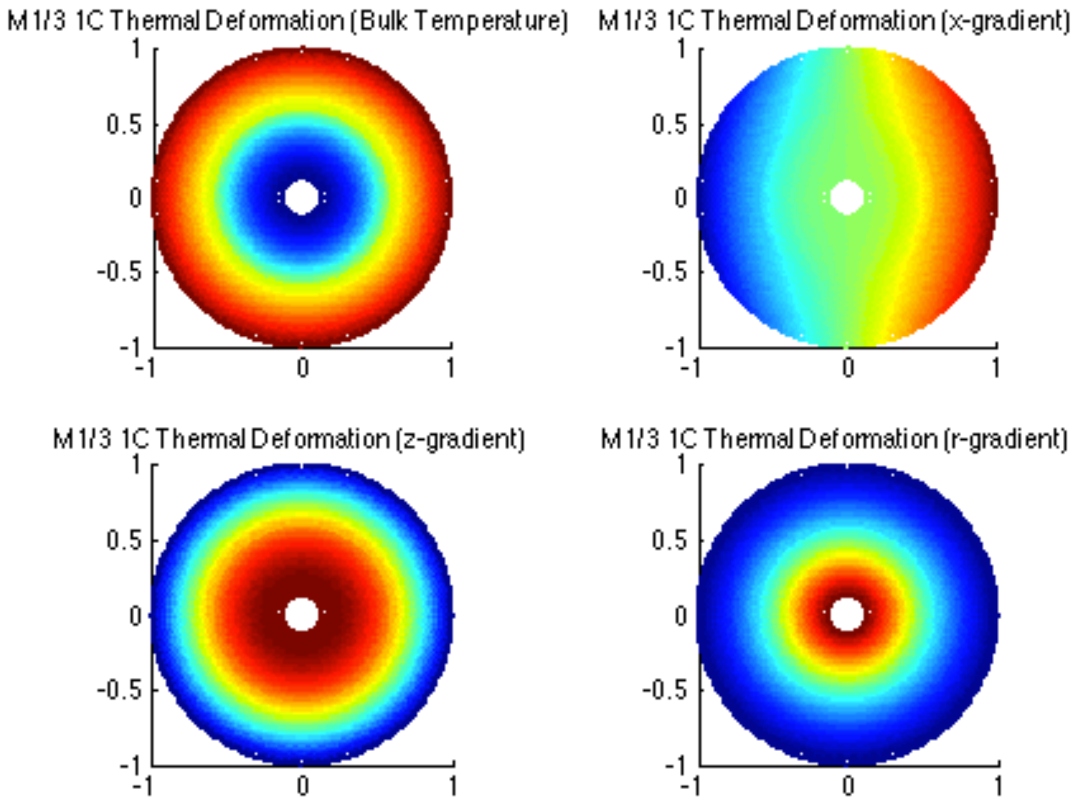

From M1M3 Finite Element Analysis

M1M3 thermal control maintains the mirror bulk temperature and the thermal gradient:

Bulk (relative to ambient) :	0.8 °C
Z-direction	0.1 °C
Radial	0.1 °C
X- and Y- direction	0.4 °C

Use Gaussian random numbers in simulations, where [-σ,σ] covers the range defined by the numbers on the left.

M2 Gravitational & Thermal Errors

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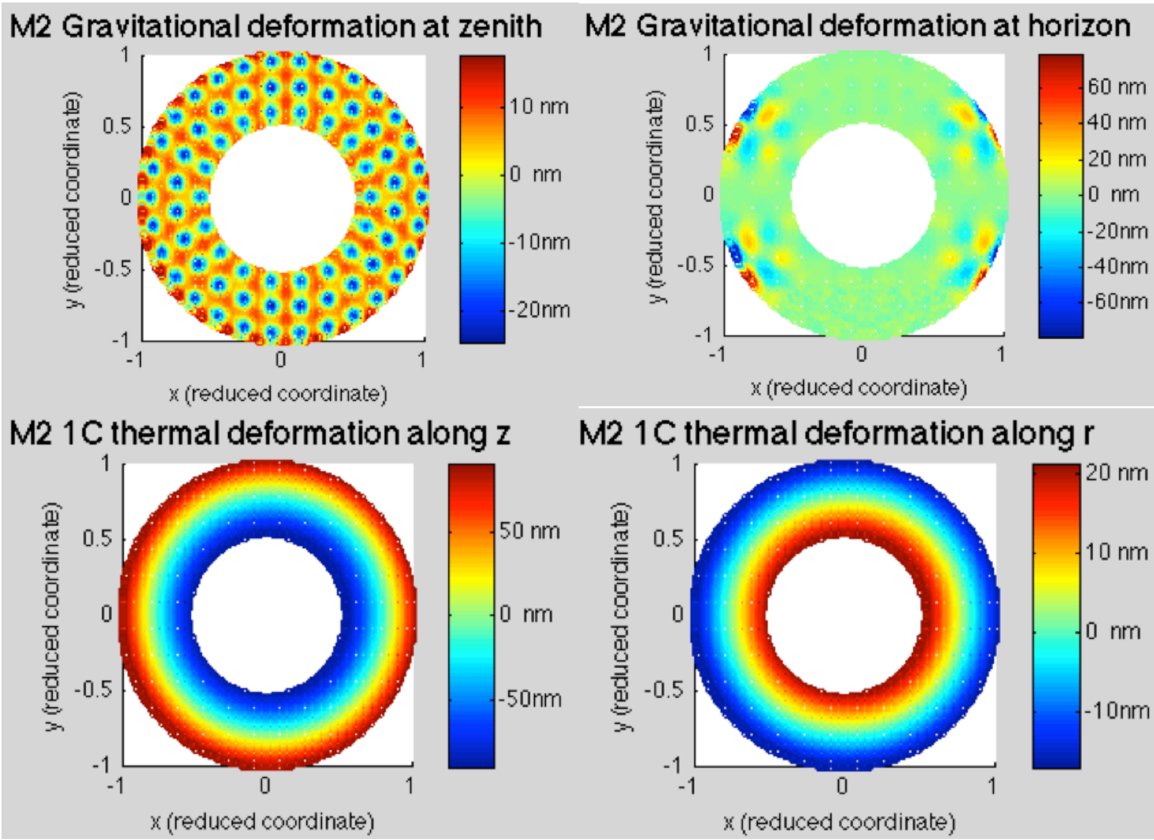

From M2 Finite Element Analysis (M2 is fabricated face-down)

M2 z- and radial thermal gradients are up to 1 ^{o}C.

We use Gaussian random numbers, whose [-σ,σ] range spans 1 ^{o}C.

- Bulk temperature and x- and y-gradients contributions negligible

M2 Coefficient of Thermal Expansion is 1% of M1M3

M2 therefore does not have thermal control

M2 surface deformation much smaller than M1M3

M2 & Camera Rigid Body DOFs

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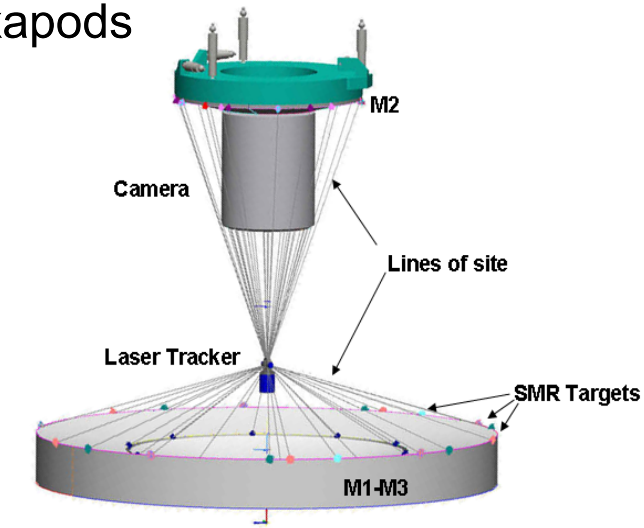
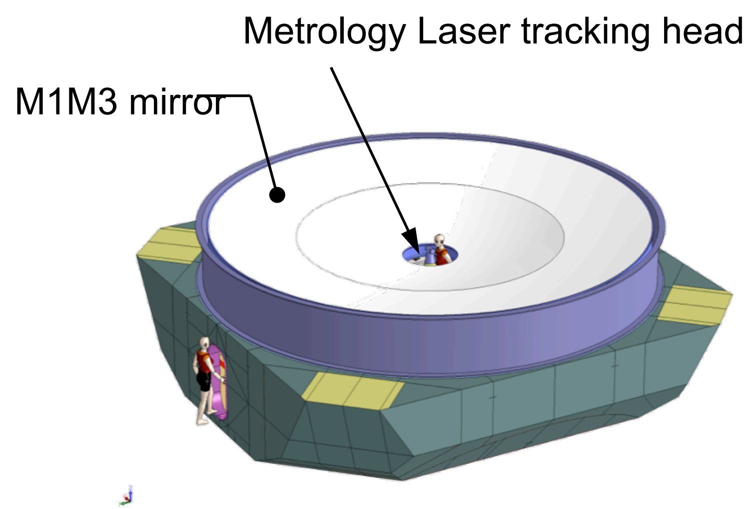
Only operated when Camera not imaging

Used to estimate the initial positioning error of the M2 and camera hexapods





Laser Tracker Uncertainty Analysis:
(used as standard deviation for Guassian random numbers)

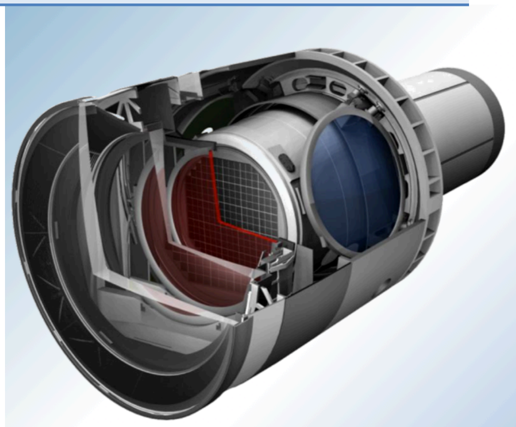
	Number of Points	Center Mag (mm) Decenter	Normal Vector (deg) Tilt	Normal Vector (arcseconds) Tilt	Center Z-component (mm) Focus
M1/M3	10	0.013	0.00023	0.8	0.009
M2	10	0.019	0.00037	1.3	0.006
Camera	10	0.011	0.00072	2.6	0.005

Camera Internal Distortions: FEA

FEA data provided by the Camera Team:

rigid body DOFs: Piston, x-,y-decenters, x-,y-,and z-tilts					
L1	L2	Filter	L3	Focal Plane	
Surface deformation described by Standard Zernikes Z4-Z28					
L1 Surface 1	L1 Surface 2	L2 Surface 1	L2 Surface 2	L3 Surface 1	L3 Surface 2

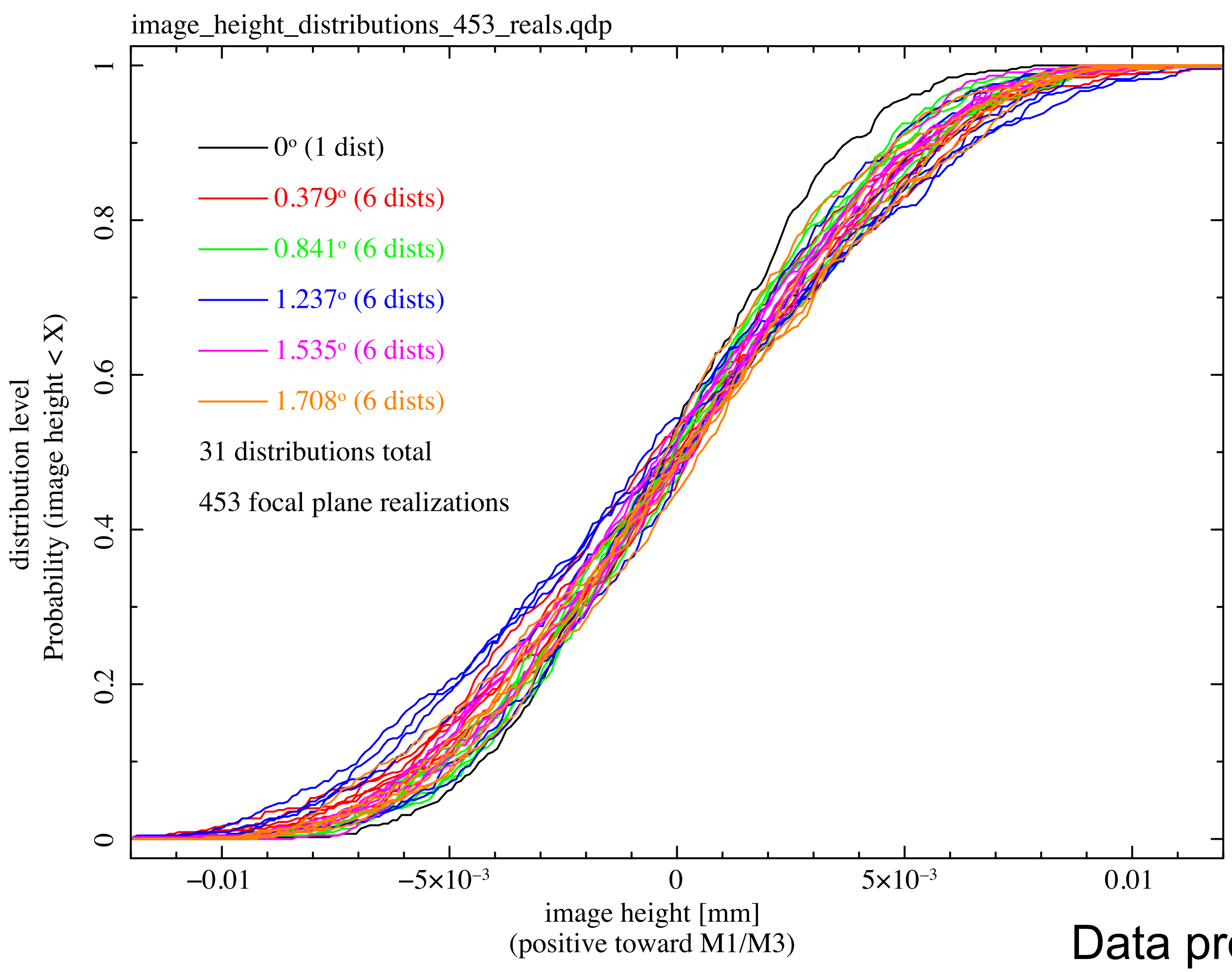
At
- Zenith and Horizon Pointings
- 0 and π/2 camera rotation
- Soak temperatures -10C, -5C, 0C, 5C, 10C, 15C, 20C, and 25C



- Rigid body displacements are typically a few tens of microns, but can be up to ~300um depending on zenith angle and camera rotation.

- The surface deformations on the two surfaces of the same lens largely cancel out.

Cumulative Sensor Height Distributions across the field



Data provided by Andy Rasumssen

Atmosphere

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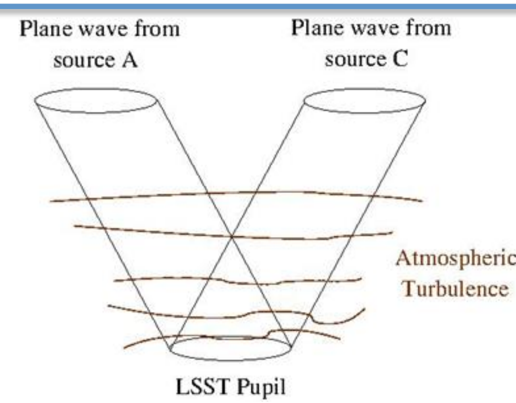
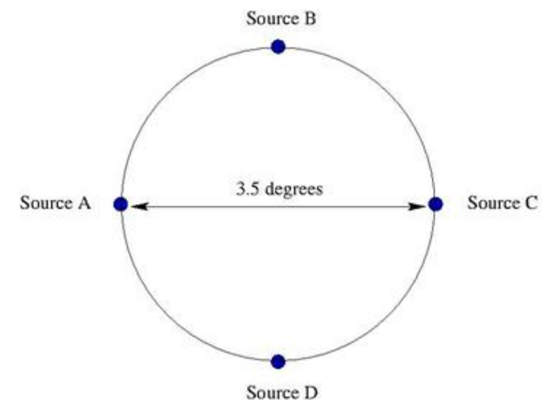
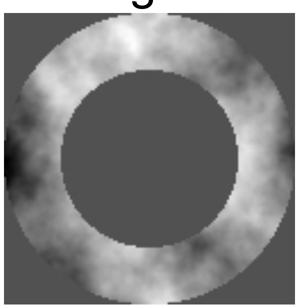
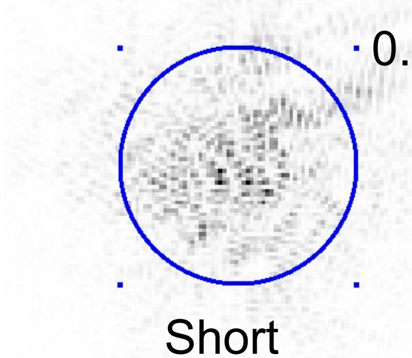
- Created using Arroyo Library (r_0=17cm, outer scale = infinity),
- 6 layers of Komogorov phase screen at various heights
- Simulated 300 Instantaneous (50ms) phase screens for each exposure
- Uncorrelated between visits, but correlated between the four corners, due to the common ground layer.



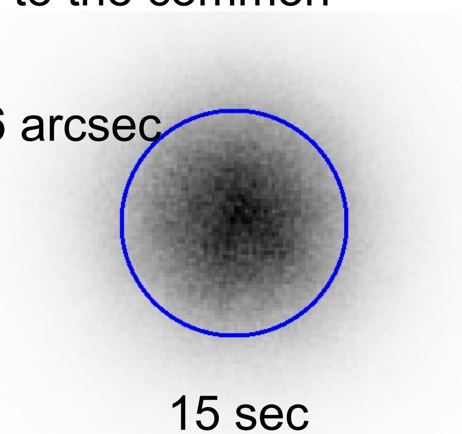




Short exposure WF Phase



Short Exposure PSF



15 sec Exposure PSF

M1M3 & M2 bending modes

M1M3 bending modes are calculated based on latest FEA analyses

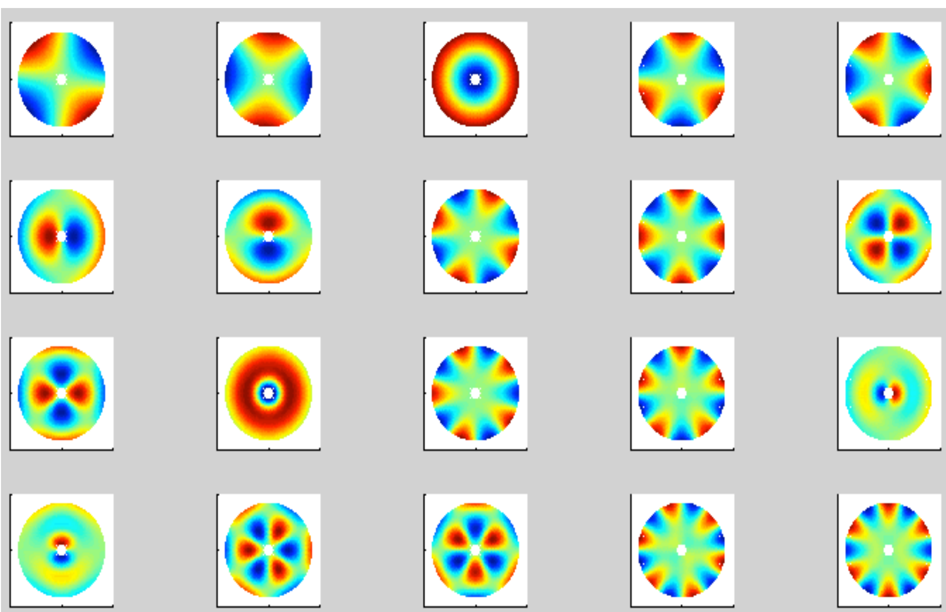
We use

20 bending modes for M1M3 substrate

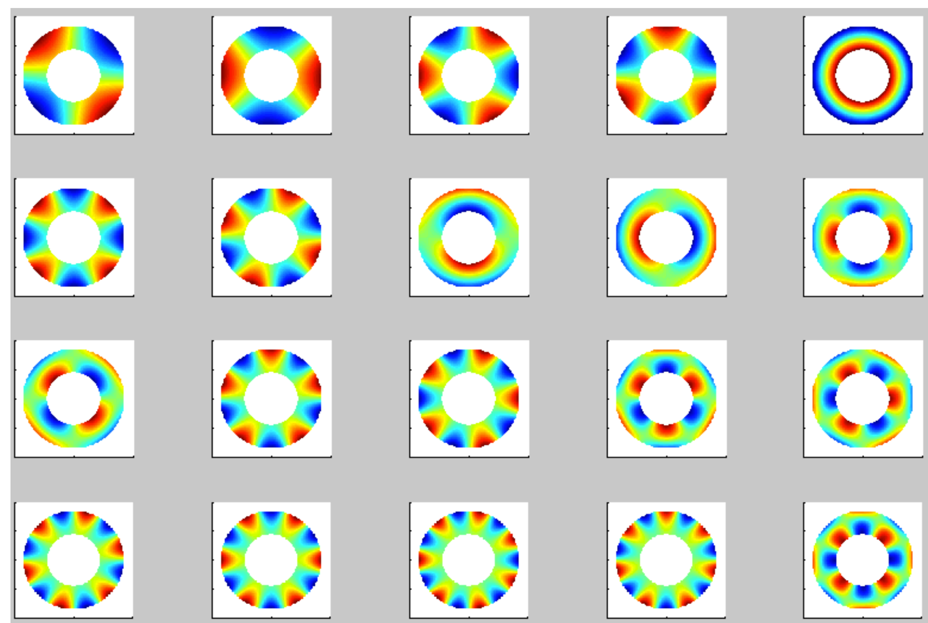
20 bending modes for M2.

For the same surface RMS, higher order bending modes require larger forces

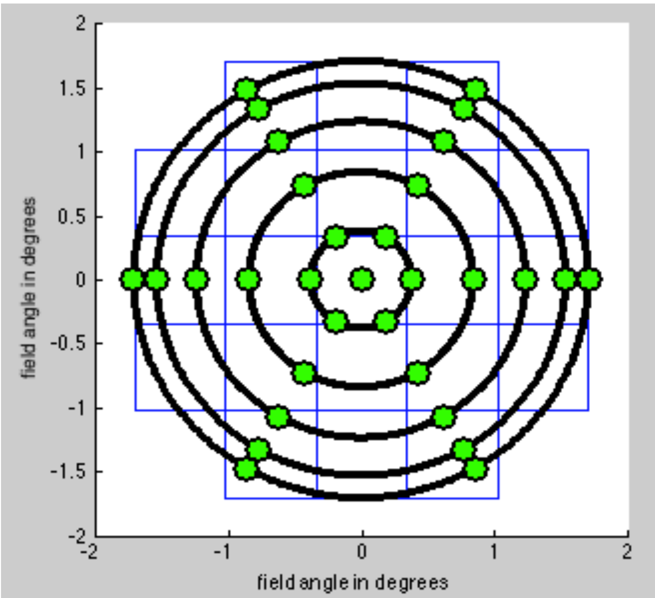
M1M3



M2



Performance Metric



- The LSST error budget on the image quality (IQ) is specified in terms of Gaussian Quadrature (GQ) of effective FWHM (FWHMeff) at a set of field positions.

- Given

$$PSSN = \frac{FWHM_{atm}^2}{FWHM_{atm+sys}^2}$$

we minimize

$$\begin{aligned} 1 - GQ(PSSN_f) &\approx 1 - \sum_f w_f \left(\prod_i (1 - \alpha_i \sigma_{fi}^2) \right) \\ &\approx 1 - \sum_f w_f \left(1 - \sum_i \alpha_i \sigma_{fi}^2 \right). \\ &= \sum_f w_f (y_f^T Q y_f) \end{aligned}$$

where
y_f is the vector of wavefront Zernikes at field *f*.
ω_f is the GQ weights at field *f*.
$Q=(2\pi/\lambda)^2 O$, *O* is a diagonal matrix whose diagonal elements are α_i.

Optimal Control

Large Synoptic Survey Telescope

- Optimize both the IQ across the field and the motions of the control variable

$$J = y^T Q y + \rho u^T H u$$

- ρ and the diagonal elements of H define the weights of the control motions relative to the FWHM.
- The current choices are
  - The weight on each bending mode is proportional to the force it requires
  - 1N RMS actuator force = 1um piston or decenter on M2 or camera = 1arcsec tilt on M2 or camera = 0.001 of PSSN loss

Control motion for iteration k+1

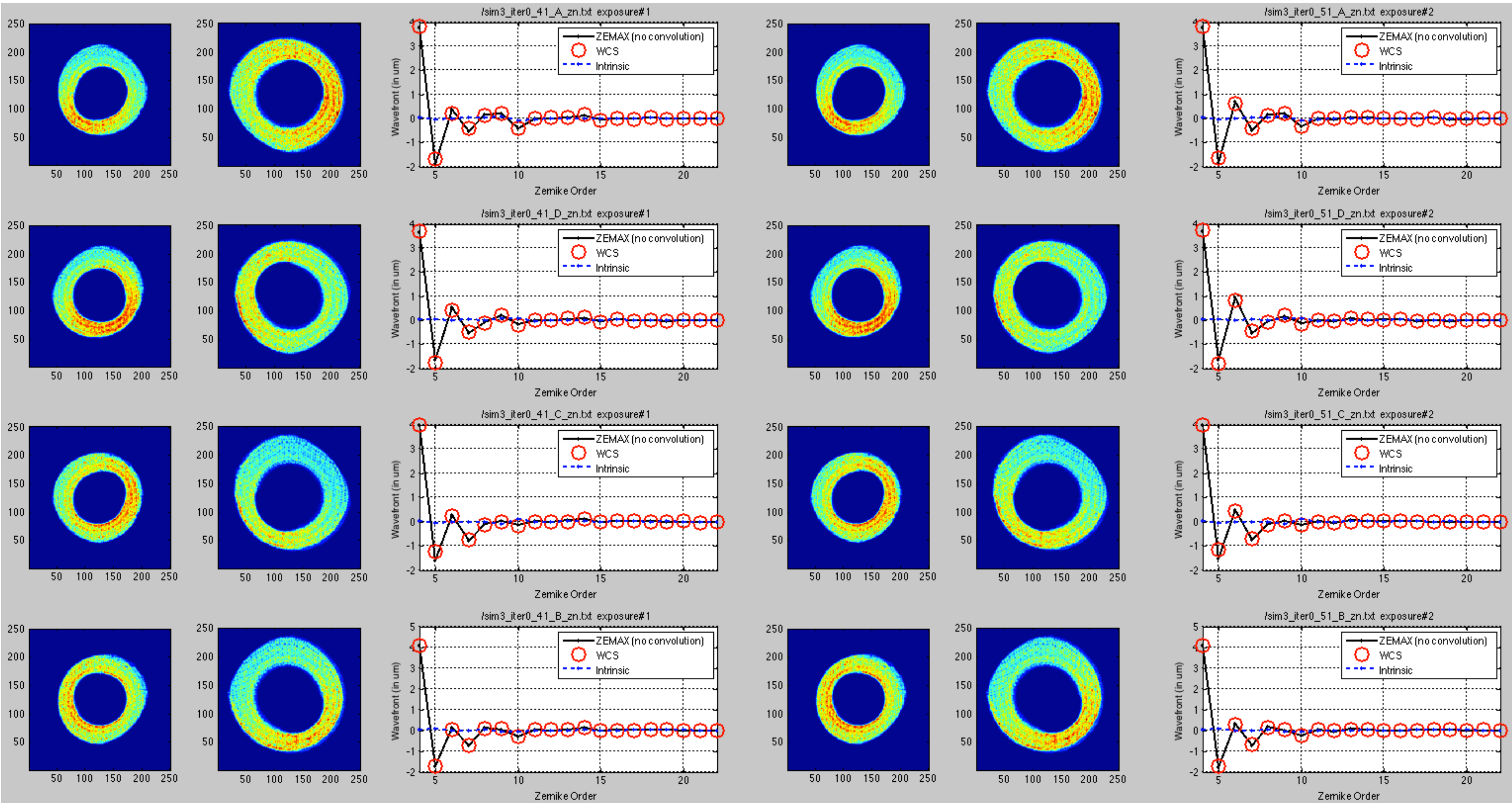
Drift due to environmental condition and operation parameters not implemented in current simulations

$$x_{k+1} = x_k + u_{k+1} + d_{k+1}$$

$$u_{k+1} = \alpha \left(A^T Q A + \rho H \right)^{-1} A^T Q A \hat{x}_k$$

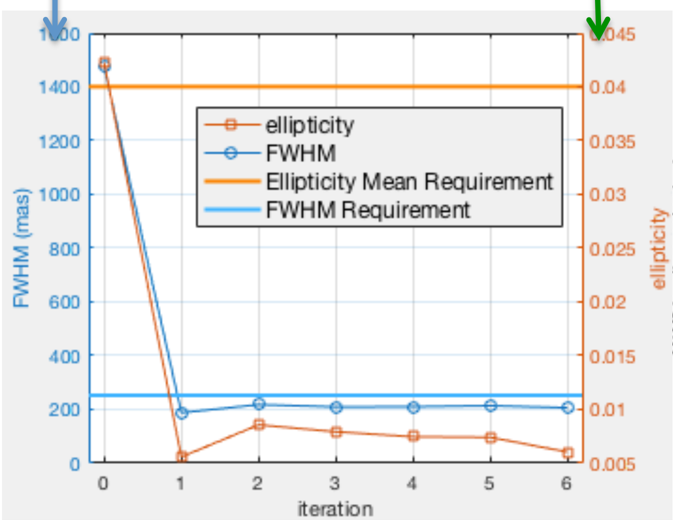
Control gain, use α<1 to integrate atmosphere over longer time.

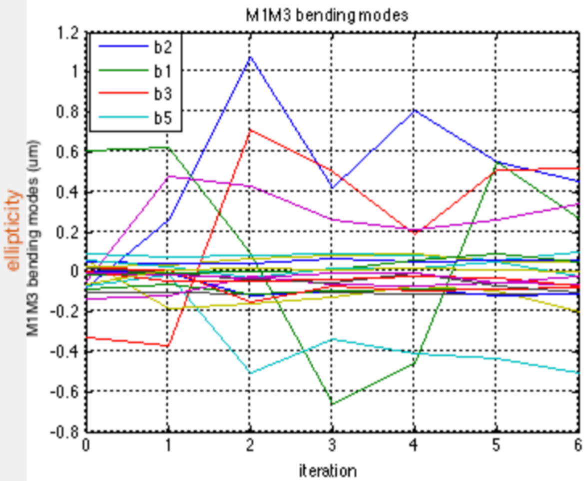
Example: WFS Algorithms at Work

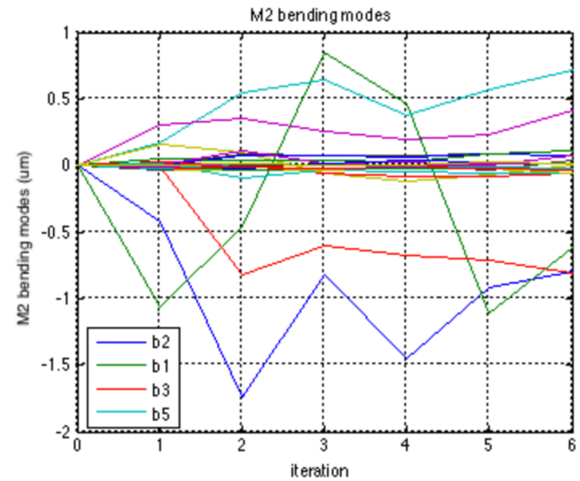


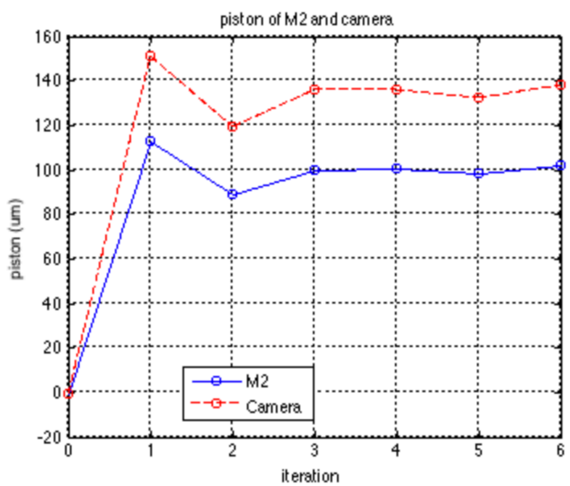
Results from One Simulation Run

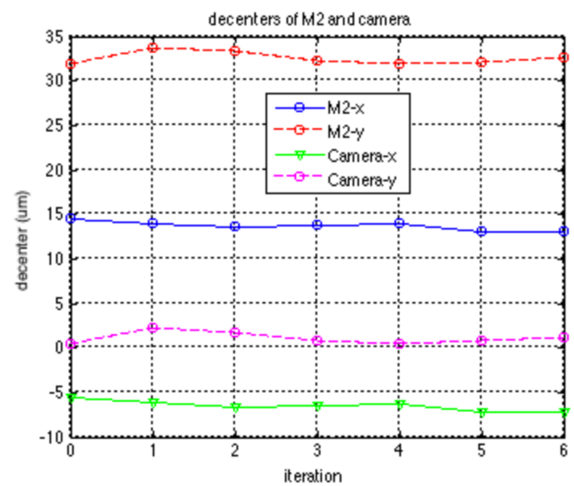
FWHMeff ellipticity

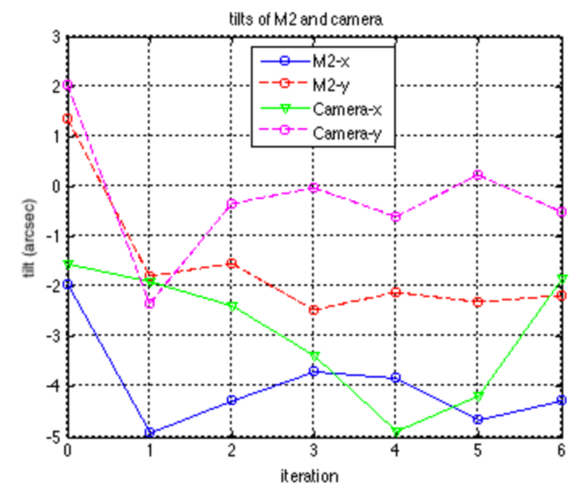












Short-comings of the Matlab-Zemax Framework

- Low speed, can not be deployed onto large clusters
- Cannot simulate full focal plane images
- Atmosphere has to be external - Arroyo
- Chromatic effects missing
- Charge diffusion and other sensor effects missing

- Still, we need a model which can accept perturbations
  - Fabrication errors/alignment errors/thermal deformations/gravity effects/dynamic noise and vibrations/environmental conditions incl. atmospheric parameters
- In Early 2015, SysEng decided to start transitioning to the Python +Phosim based framework.
- Our strategy: only trust the analysis results after fully validating relevant features of our simulation tools.

Work Related to This Transition

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- Conversion of related code into Python
  - Wavefront sensing code (together with Andy Connolly)
  - AOS control related code
  - Image quality metric related code
- Active participations in Phosim validation discussions
  - Atmosphere (wavefront variance, astrometric residual, and more)
  - Sensor physics

- OPD validation
- Perturbation validation
- Sensitivity matrix validation

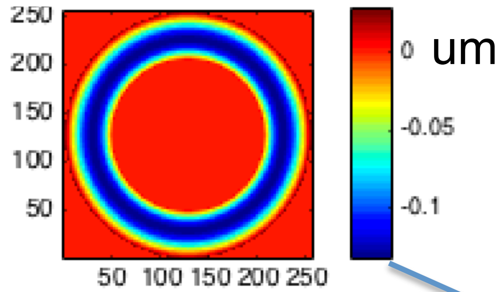
Discussed in more detail next

New analyses that utilize the new framework:

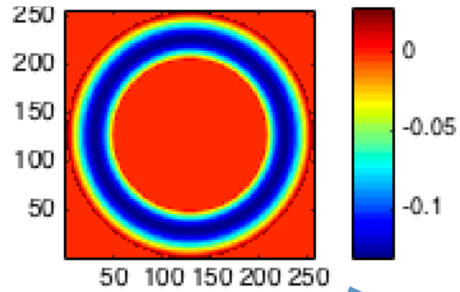
- Simulation and optimization of AOS control (in progress)
- Wavefront sensor offset trade study
- Wavefront sensor midpoint position trade study

Example of OPD Validation

Calculated/Zemax



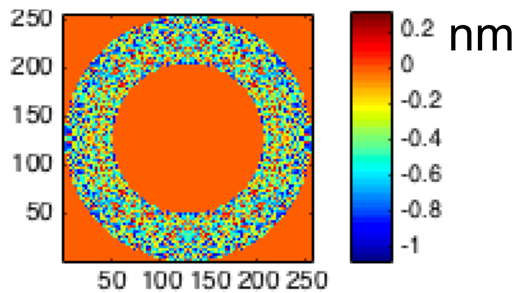
Phosim

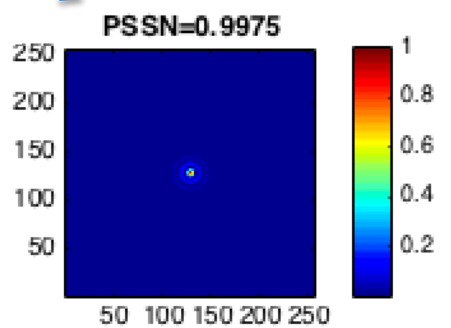


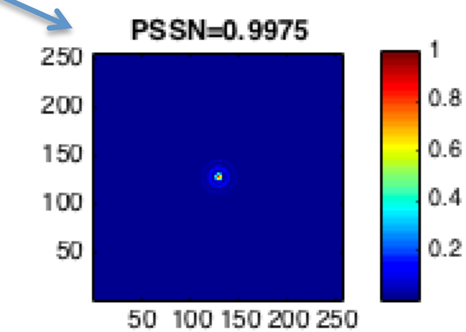
On optical axis

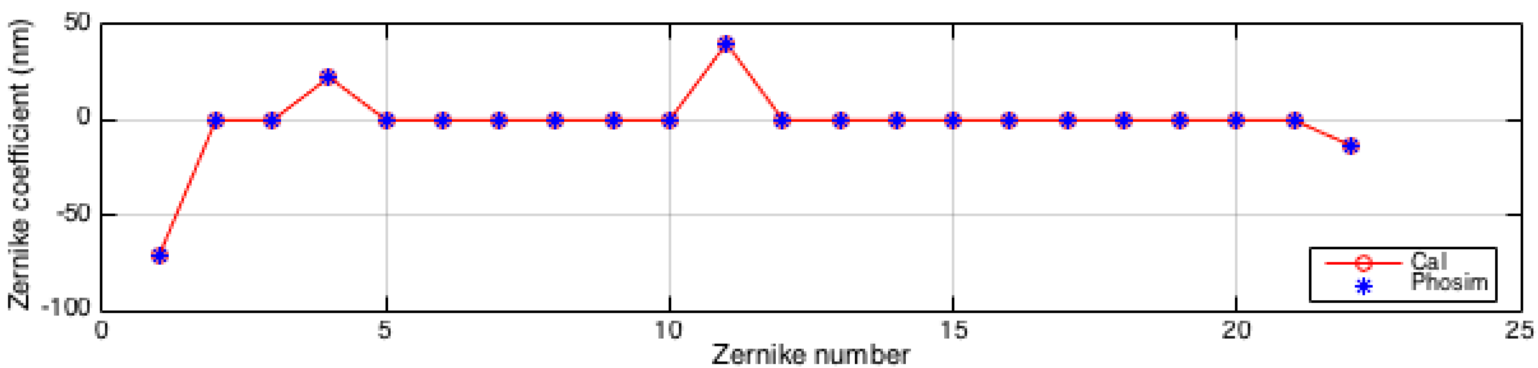
Calculated:
Calculated using Zemax ray-hit coordinates on each optical surface, and validated against Zemax OPD output

Difference

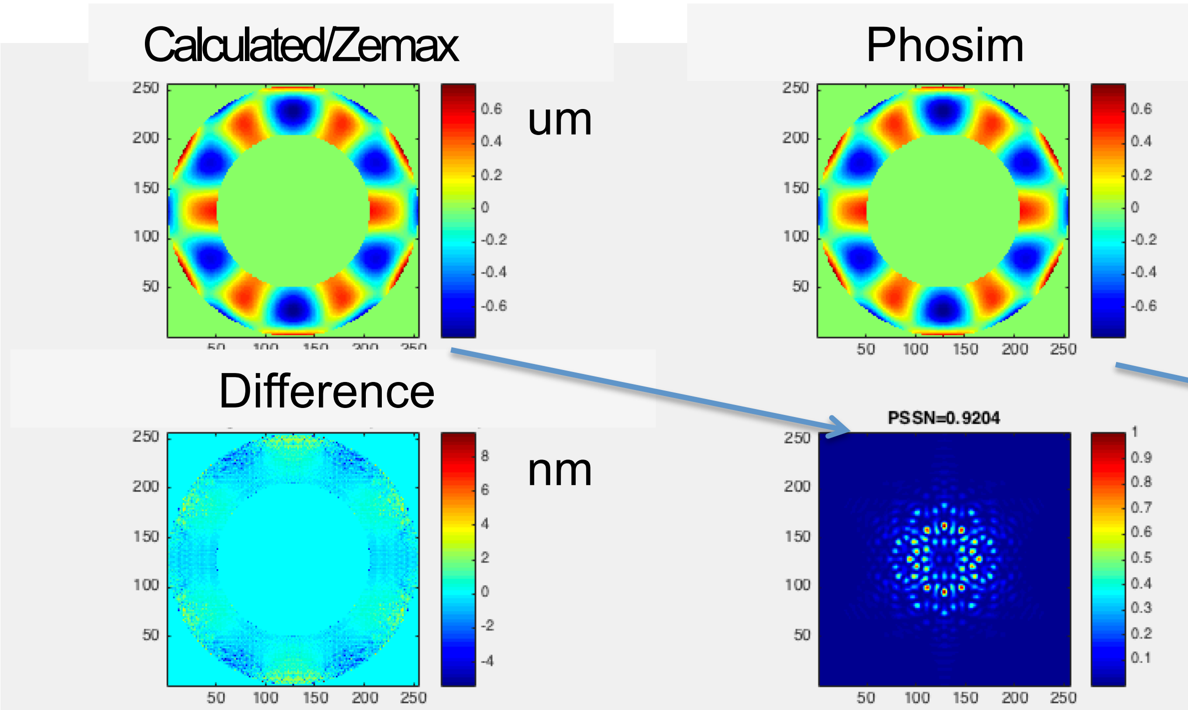






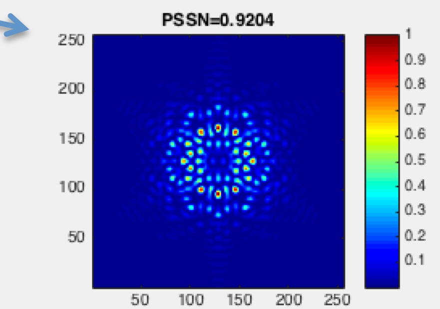


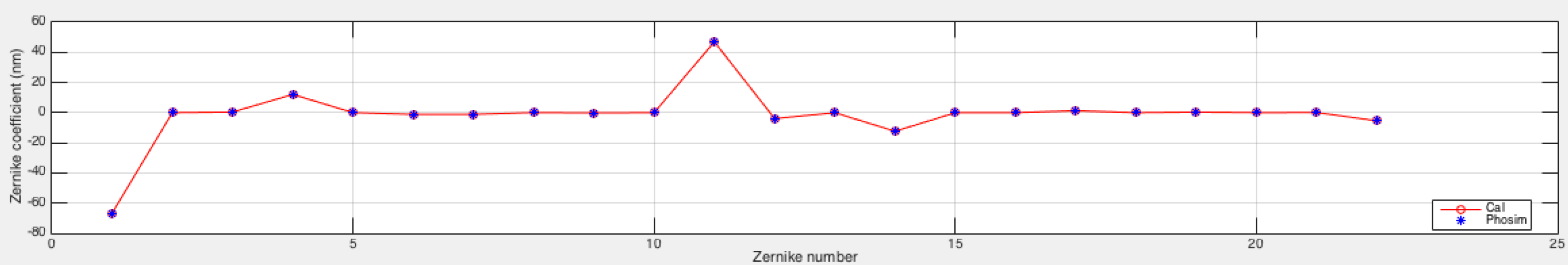
Example of Perturbation Validation



M1M3 bending mode #20

Calculated:
Calculated using Zemax ray-hit coordinates on each optical surface, and validated against Zemax OPD output





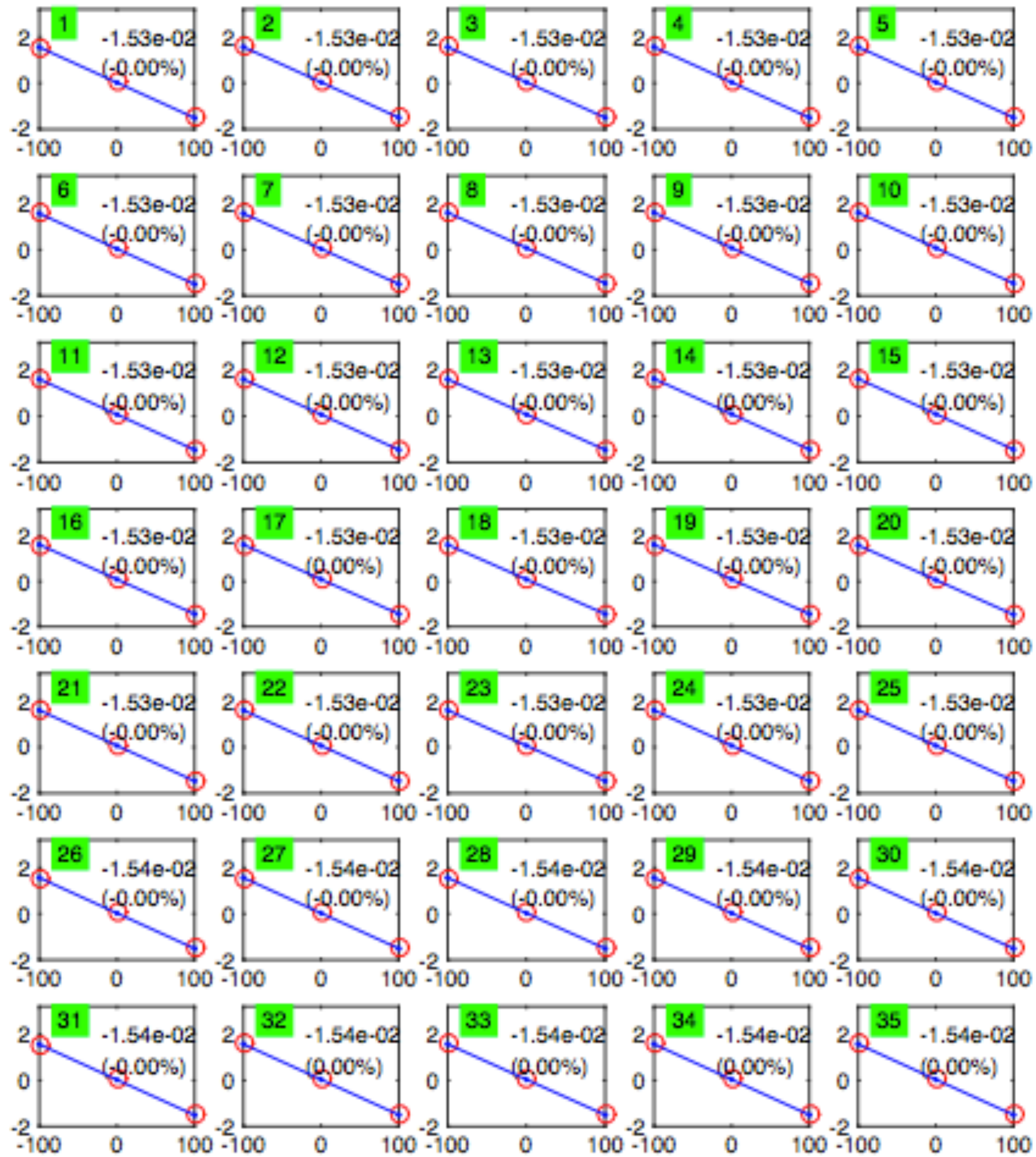
Sensitivity Matrix Validation

Z4 (in um) as a function of M2_piston (in um)

Loop over all DOFs

Loop over Z4-Z22

35 field points



Plots show the validation of 35 sensitivity matrix elements out of the 35 (field points) x 19 (z4-z22) x 50 (DOF) = 33250 sensitivity matrix elements.

These are now part of the Phosim automated unit test pipeline, which is run every a few days.

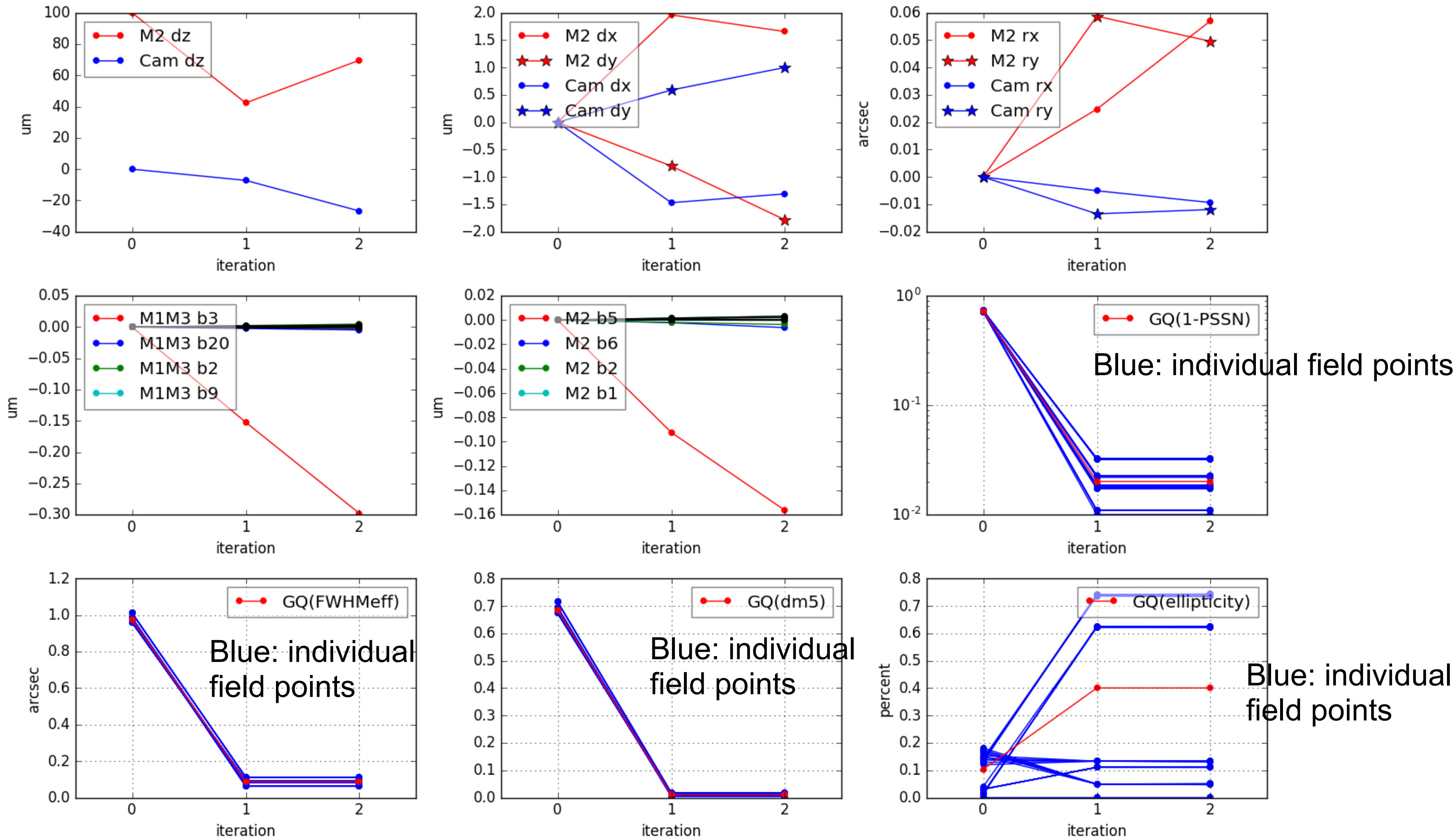
Validates almost everything related to optics:

- OPD calculation itself
- raytrace components,
- optical design implementation
- perturbation file interfaces
- Interpolation methodologies
- sign conventions
- etc.

Closing AOS loop under Python+Phosim framework

Example: initial condition: M2 piston 200um; no thermal and gravity deformation

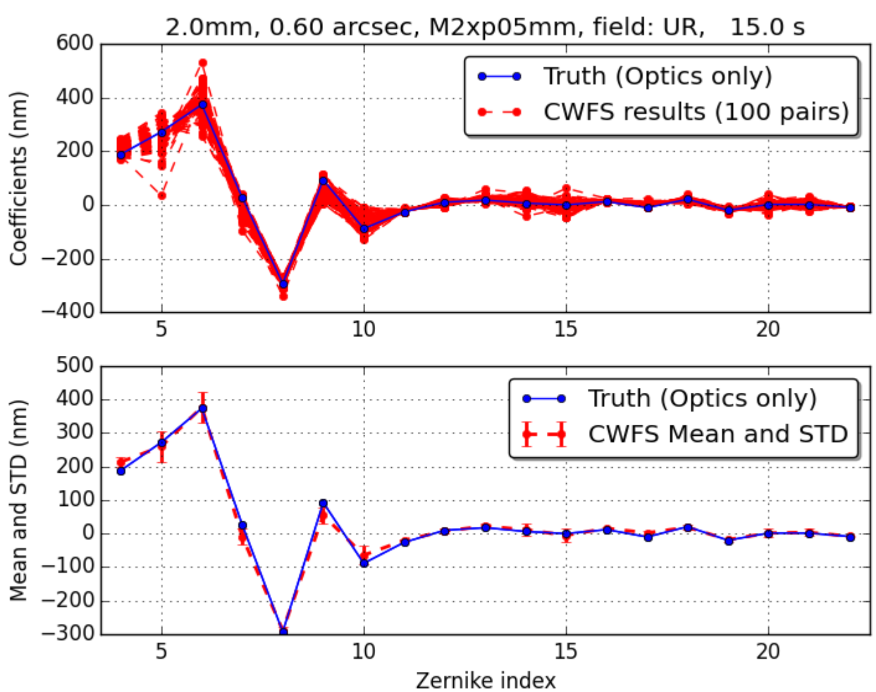
Some details of the AOS control strategy still under testing

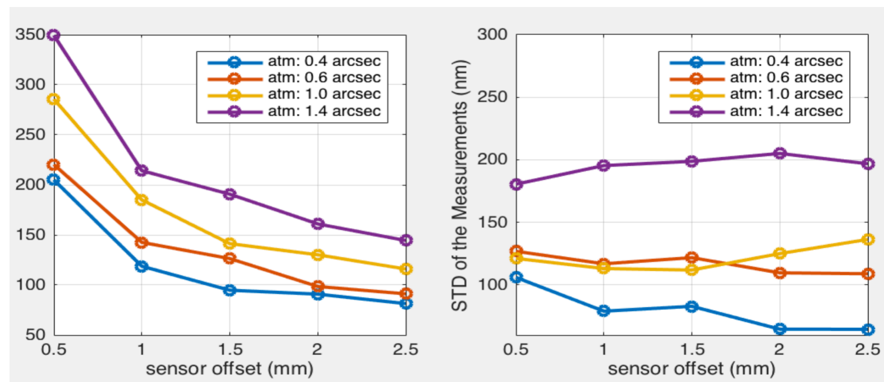


Wavefront Sensor Offset Trade Study

Table 1 Variables used in the Monte Carlo study of the wavefront sensing performance.

Variables	Values
Sensor offset	0.5, 1.0, 1.5, 2.0, 2.5mm
Atmospheric FWHM	0, 0.4, 0.6, 1.0, 1.4 arcsec
Random seed (for atmosphere)	5 independent atmosphere realizations
Optics state	Unperturbed; M2 x-decenter; M2 x-tilt
Wavelength	500nm, 770nm, r-band
Field	Field center; R44_S00
Exposure time	1, 15, 150s
Detector	Default; Perfect; basic physics only





Deviation from truth gets smaller with larger offset and better atmosphere.

Variance doesn't change much with offset, but gets smaller with better atmosphere.

Wavefront Sensor Midpoint Positioning Trade Study

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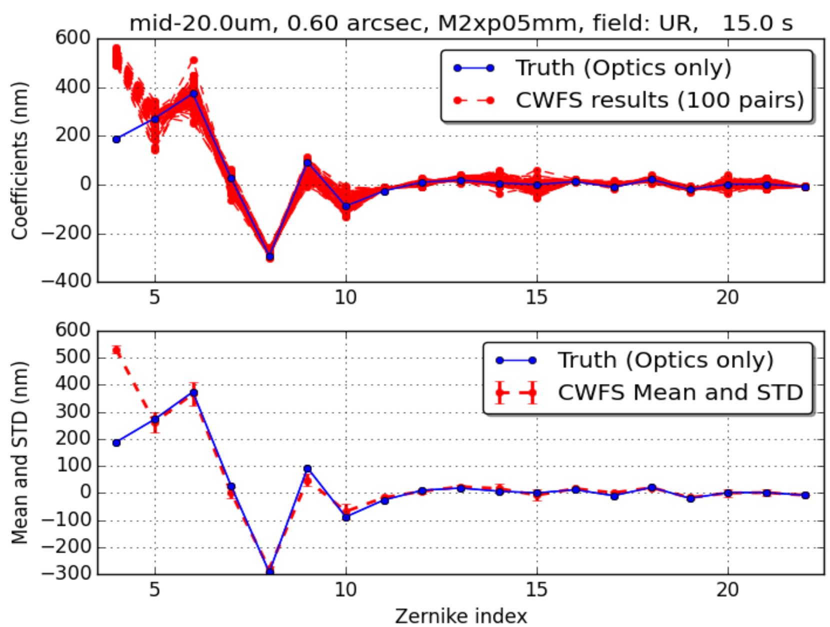
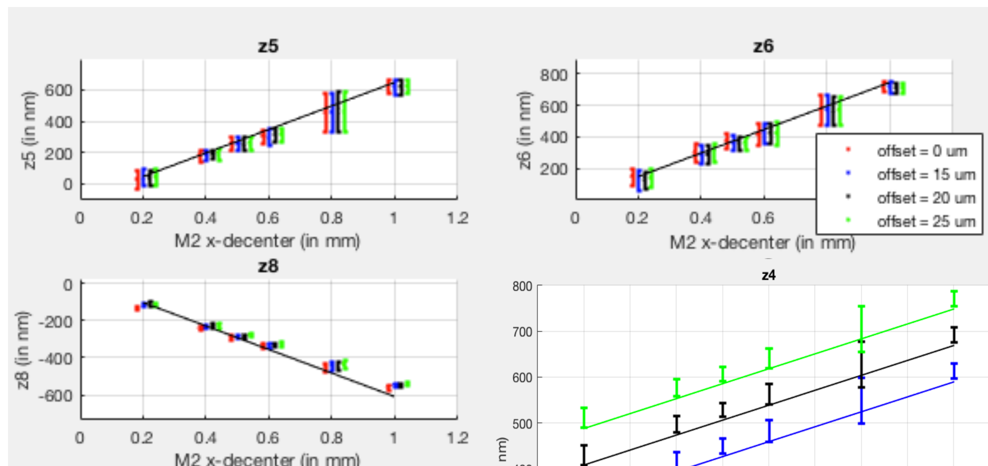
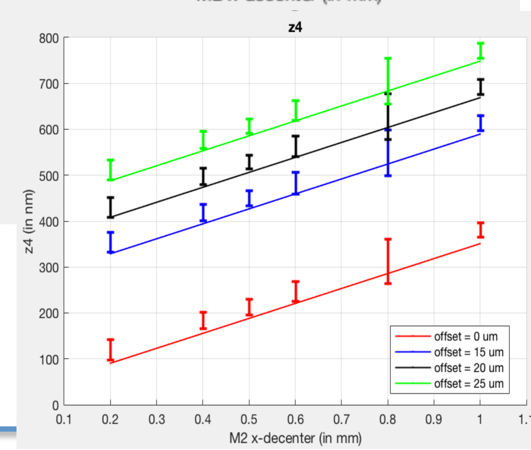
Table 1 Variables used in the Monte Carlo study of the wavefront sensing performance. "*" indicates values that we vary in this analysis.**

Variables	Value
***Midpoint offset	0, 15um, 20um, 25um
Sensor offset	2.0mm
Atmospheric FWHM	0.6 arcsec
***Optics state	M2 x-decenter by 0.2, 0.4, 0.5, 0.6, 0.8mm
Wavelength	r-band (wavefront truth is for effective wavelength: 622nm)
Field	R44_S00
Exposure time	15s
Detector	Default; with charge diffusion and sensor effects





25um midpoint offset seems tolerable



Summary & Future Work

The Project SysEng team has built an integrated model of the LSST, using our best knowledge of the as-built system. We will keep updating the model with latest information as the construction progresses.

We now use this model routinely for evaluating change and deviation requests. The model will be useful in future trade studies, commissioning, and for understanding systematics in scientific analyses such as weak lensing.

In the past ~1.5 years, SysEng Spent significant effort working with Phosim,

- validate features we need
- Improve Phosim user interfaces
- Use Phosim for SysEng analyses, and make engineering decisions based on those analyses.

We plan to continue using Phosim in the coming years, including for commissioning simulations

Caveat: only use a Phosim feature after it has been validated.