Optomechanical Design and Analysis of Adaptive Optical Systems using FEA and Optical Design Software

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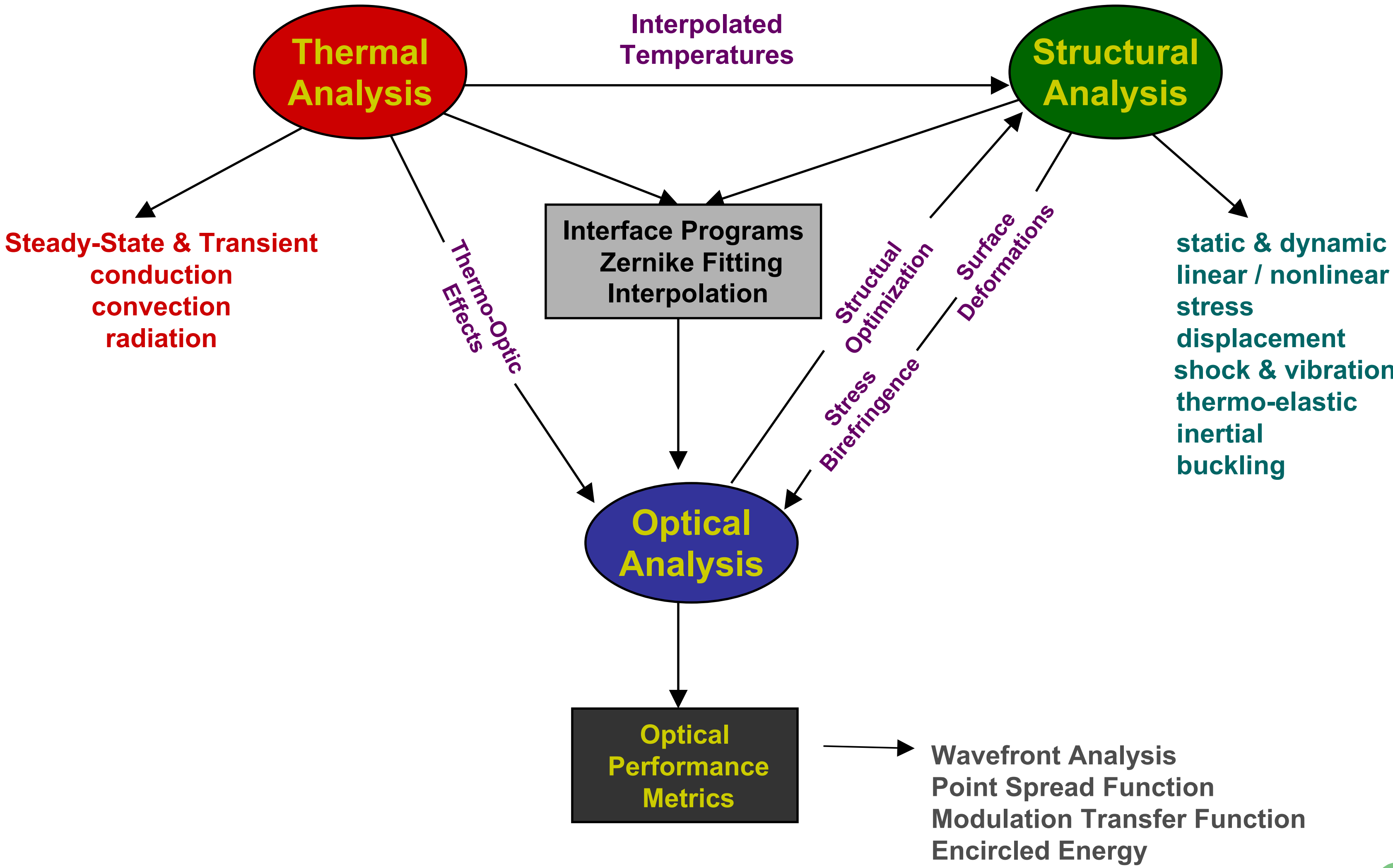
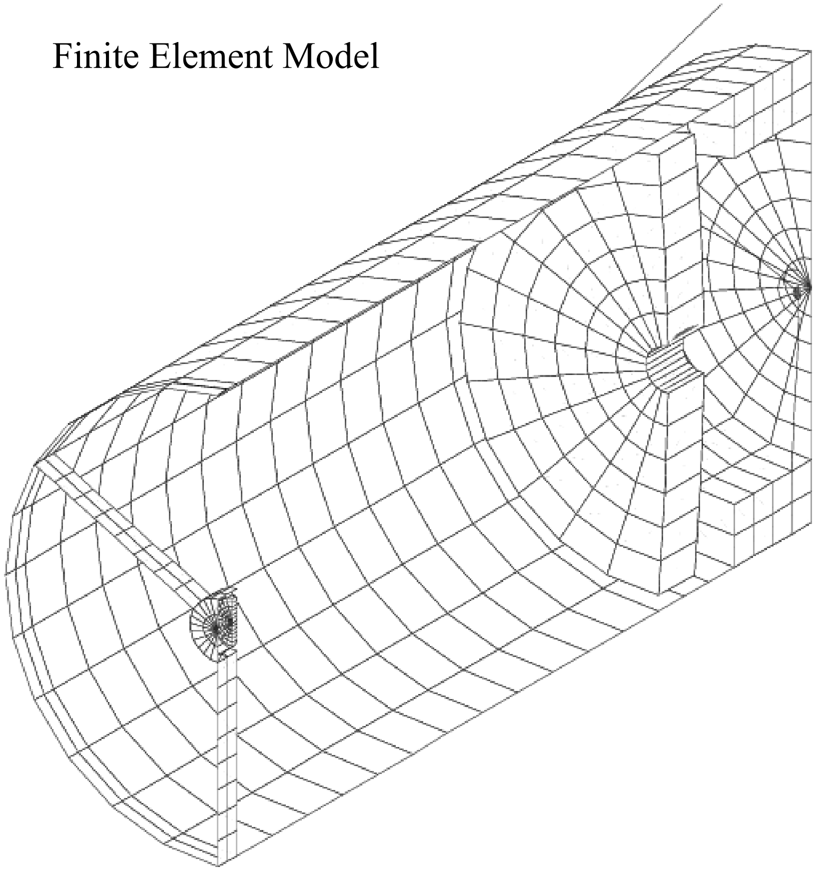
Integrated Optomechanical Analysis



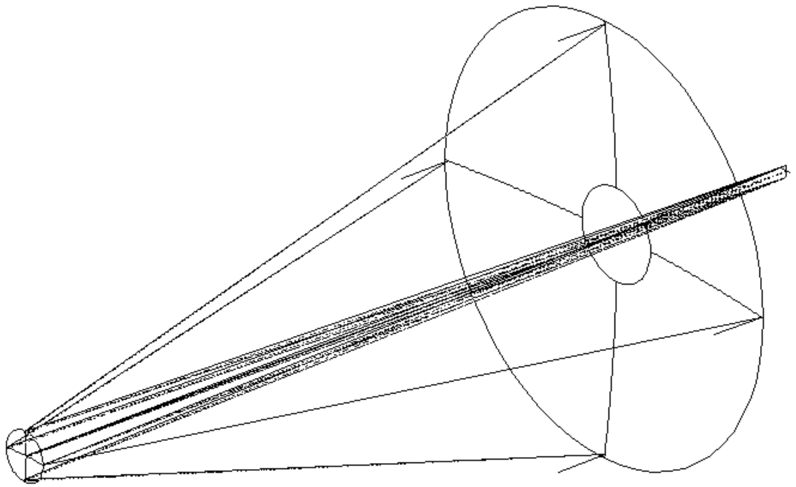
Integrated OptoMechanical Analysis

Example Telescope: Must pass structural distortions to optical model for analysis

Finite Element Model

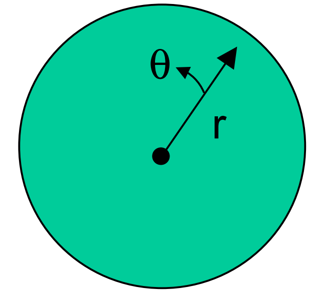


Optical Model



Zernike Polynomials

- **Polynomial series with two real variables, r and θ**



$$\Delta Z(r,\theta) = A_{00} + \sum_{n=2}^{\infty} A_{n0} R_n^0(r) + \sum_{n=1}^{\infty}\sum_{m=1}^{n} R_n^m \left[A_{nm}\cos(m\theta) + B_{nm}\sin(m\theta)\right]$$

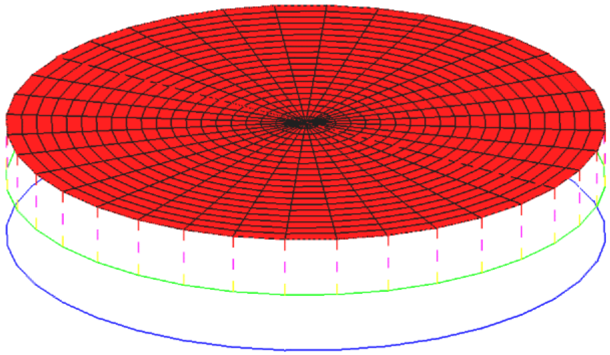
$$R_n^m(r) = \sum_{s=0}^{\frac{n-m}{2}} (-1)^s \frac{(n-s)!}{s!\left(\frac{n+m}{2}-s\right)!\left(\frac{n-m}{2}-s\right)!} r^{(n-2s)}$$

r - dimensionless normalized radius
θ – polar angle
A_{nm} & B_{nm} - polynomial coefficients

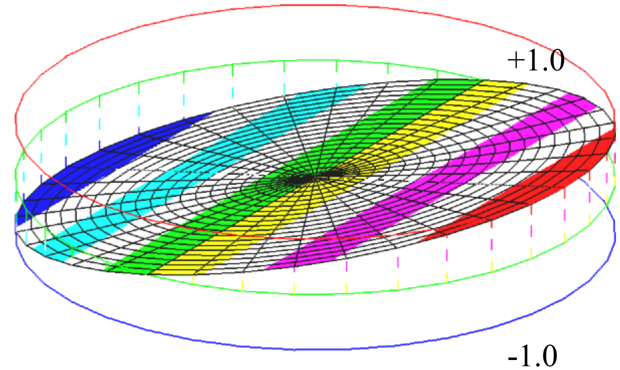
- Standard Zernike polynomials (See Born & Wolf, *Principles of Optics)*
  - use as many terms as required to represent the data

- Fringe Zernike polynomials are a subset of the Standard Zernikes
  - include higher-order symmetrical terms (r^{10} & r^{12}) that are more important to wavefront propagation; eliminates the higher-order azimuthal terms

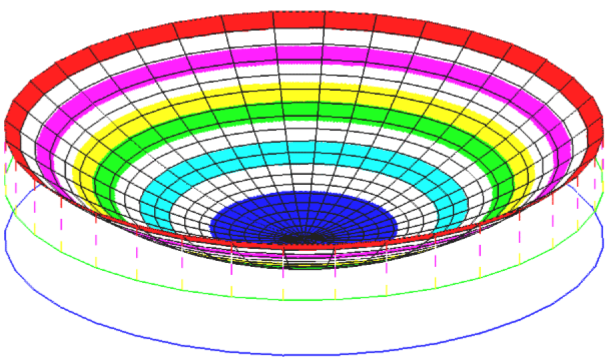
Zernike Surfaces



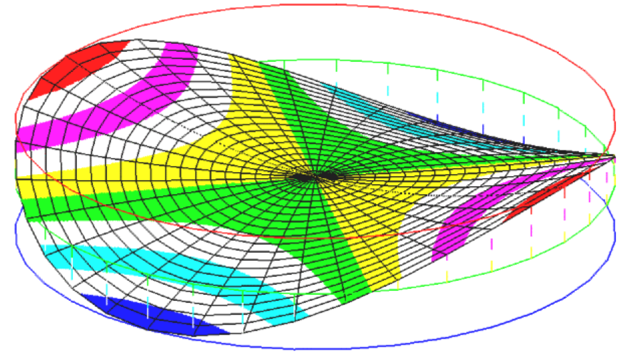
Bias/Piston: 1



Tilt: $r\cos(\theta)$ / $r\sin(\theta)$

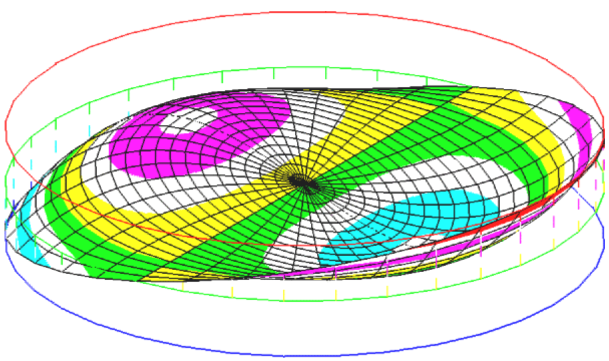


Power/Defocus: $2r^2-1$

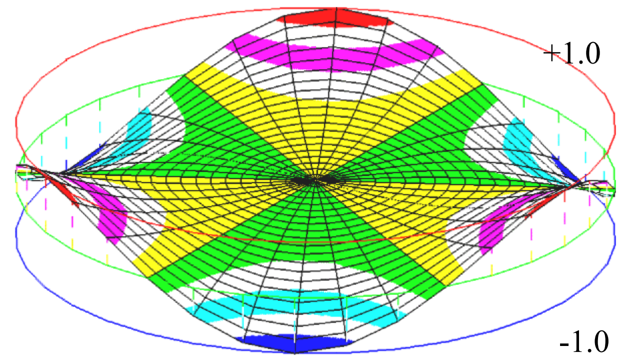


Pri-Astigmatism
$2r^2\cos(2\theta)$ / $2r^2\sin(2\theta)$

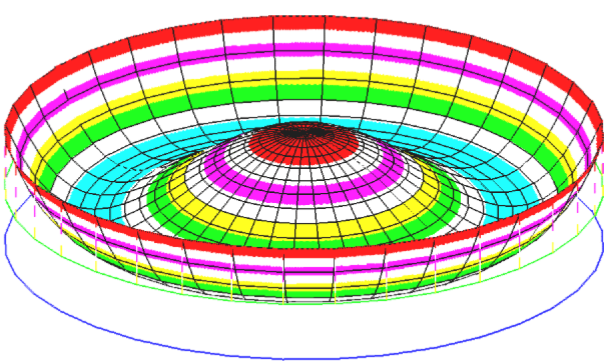
Zernike Surfaces



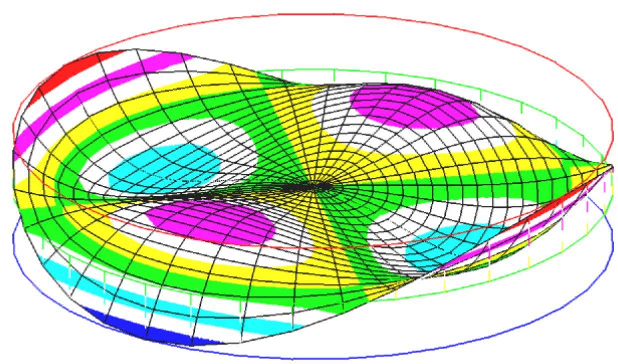
Pri-Coma:
$(3r^3-2r)\cos(\theta)$ / $(3r^3-2r)\sin(\theta)$



Pri-Trefoil:
$r^3\cos(3\theta)$ / $r^3\sin(3\theta)$



Pri-Spherical:
$6r^4-6r^2+1$



Sec-Astigmatism:
$(4r^4-3r^2)\cos(2\theta)$ / $(4r^4-3r^2)\sin(2\theta)$

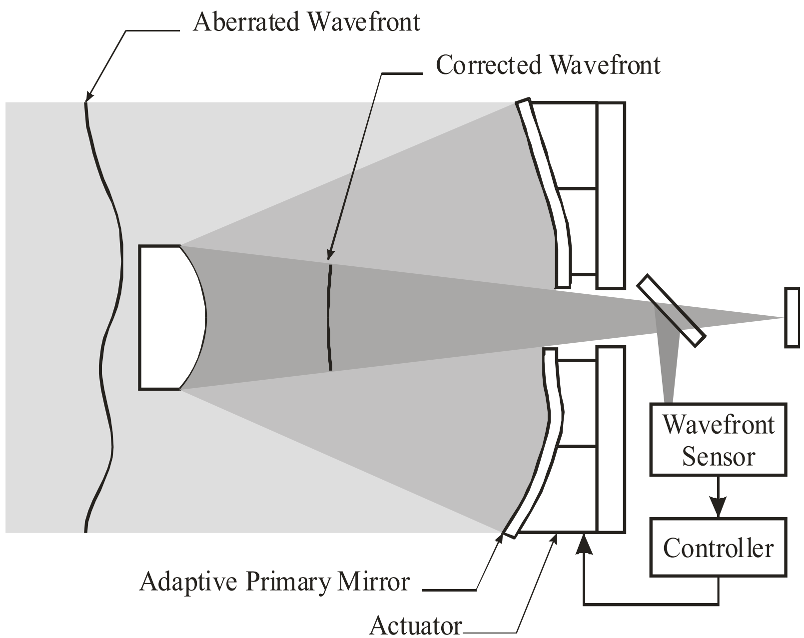
Integrated OptoMechanical Analysis - *Current Technology*

- FEA code (Nastran) => surface deformations
- SigFit => Fit Zernikes to FEA data, output in Optics format
- Optics code (CodeV) => read Zernikes, calculate system optical response

- Disadvantages
  - requires optical engineer in the loop
  - analysis process turnaround is slow
  - can not use in FEA optimization loop

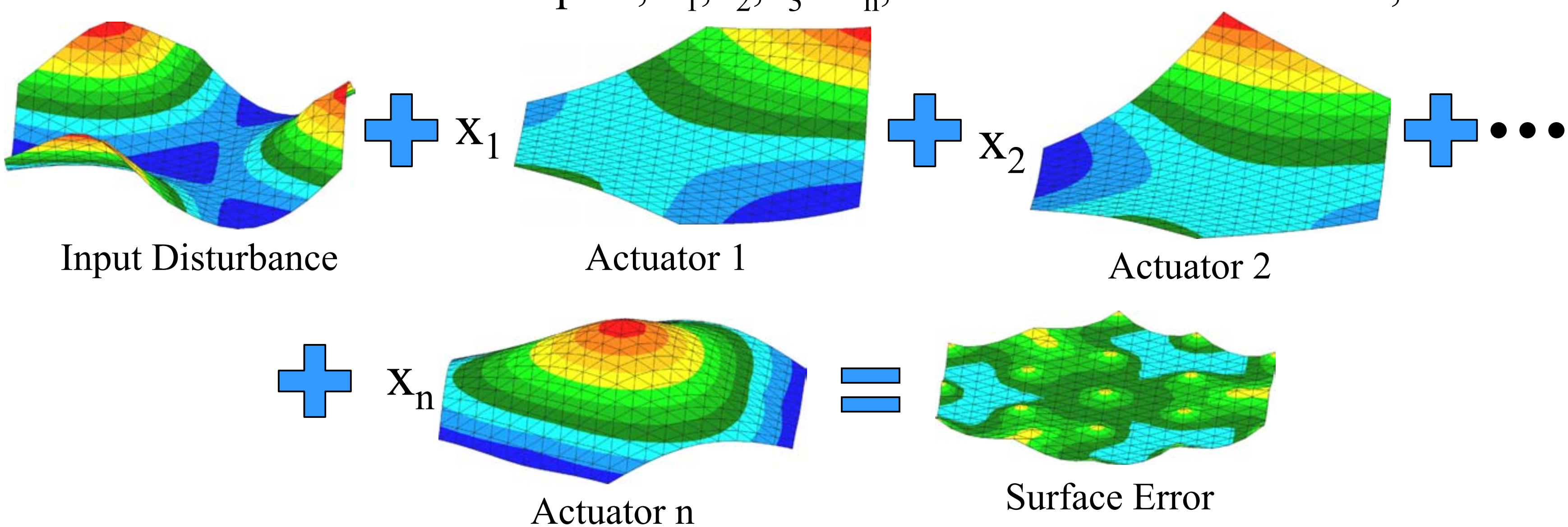
Why Adaptive Optical System

- Optical surfaces are deformed and moved based on measured or anticipated information to compensate for unwanted disturbances
- Uses
  - Fabrication & assembly errors in deployable systems
  - Thermoelastic & humidity distortion
  - Atmospheric disturbance in ground based telescopes
  - Vibrations & dynamic disturbances



Adaptive Simulation Method - Conceptual

- Adaptive Performance Can Be Simulated With Finite Element Analysis
  - Generate two sets of deformation predictions
    - Uncorrected disturbances
    - Actuator influences
  - Solve for actuator inputs, $x_1,x_2,x_3...x_n$, to minimize surface error, E



  - If focus compensation exists elsewhere, terms like $2\rho^2$-1 or ΔR can be added as *augment* actuators

Adaptive Analysis - *Current Technology*

- FEA code => surface distortions
- FEA code => actuator influence functions
- SigFit => read FEA data, calculate actuator force to correct that surface
- Optics code => read SigFit data, calculate system response

- Disadvantages
  - Error correction for that single surface, not system response
  - Not correcting other optical surfaces effects
  - Can not combine multiple adaptive surfaces

- To correct system level effects, the system wavefront error must be related back to the adaptive optic as an equivalent surface distortion.

Integrated System Analysis - *New Technology*

- Optics code => system response sensitivity due to unit Zernikes at each surface
- FEA code => surface distortions of all surfaces
- FEA code => influence functions for all actuators (if adaptive)

- SigFit => calculate system response
  - fit Zernikes to FEA distortions of each surface
  - multiply by system sensitivities to get system response

- SigFit => calculate corrected system response (if adaptive)
  - fit Zernikes to FEA influence functions
  - calculate actuator forces to minimize system error

- Advantage
  - speeds up analysis turn around
  - using system level performance generates superior designs

Integrated System Analysis - *New Technology*

- Optical surfaces: n = 1 to S
- Zernike in/surface: j = 1 to Z
- Load case number: i = 1 to L

Number adaptive surfaces: t = 1 to T
Zernike out/system: k = 1 to Z
Actuator number: m = 1 to M

- Sensitivity matrix = Zernike out (k) for Zernike in (j) at surface (n) = S_{kj}^{n}
- Disturbance fit = fit each load case (i) with Zernike (j) at surface (n) = C_{ji}^{n}
- Actuator influence = fit with Zernike (j) at surface (t) = B_{jm}^{t}
- System response = Zernike (k) at output location (0) for load case (i) = Z_{ki}^{0}

Integrated System Analysis - *New Technology*

- System level response = Zernikes at output (ie Exit Pupil)

$$Z_{ki}^{0} = \sum_{n}^{S} S_{kj}^{n} C_{ji}^{n}$$

Where S is the Zernike sensitivities from Code V

S_{kj}^{n} = matrix of size (Z x Z x N)

and C is the Zernike fit to FEA deformations for each load case

C_{ji}^{n} = matrix of size (Z x L x N)

Resulting Z^{o} is reported along with Surface RMS and Peak-Valley

Output a visualization file showing net response at output location

Integrated System Analysis - Adaptive - *New Technology*

- System level response at Output location due to Actuators

$$U_{km} = \sum_{t}^{T} S_{kj}{}^{t} B_{jm}{}^{t}$$

Where B is the Zernike fit to Actuator influence functions

$B_{jm}{}^{t}$ = matrix of size (Z x M x T)

Define system level error E as

$$E = \sum_{k}^{Z} w_k \left(Z_{ki} - \sum_{m}^{M} U_{km} A_m \right)^2$$

Integrated System Analysis - Adaptive - *New Technology*

Minimize System Error with respect to Actuator forces

$$dE/dA_q = \sum_k^Z w_k 2\left(Z_{ki} - \sum_m^M U_{km} A_m \right) U_{kq} = 0$$

Solve resulting linear system for A

$$[H]\{A\} = \{F\}$$

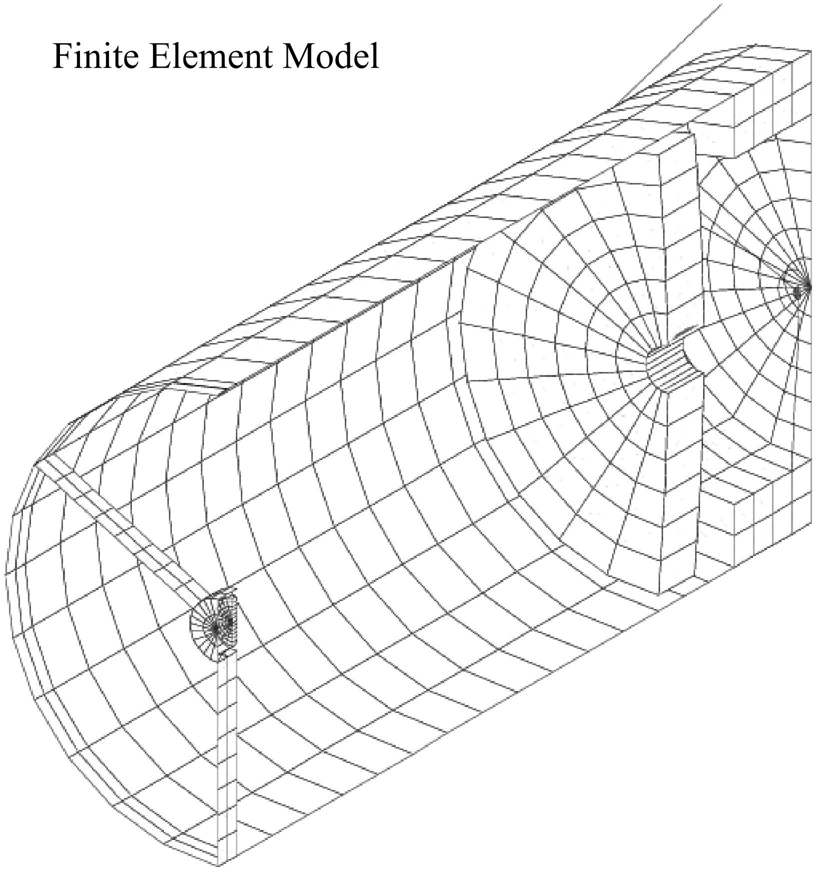
$$H_{qm} = \sum_k^Z w_k U_{qk} U_{km}$$

$$F_q = -\sum_k^Z w_k Z_k U_{kq}$$

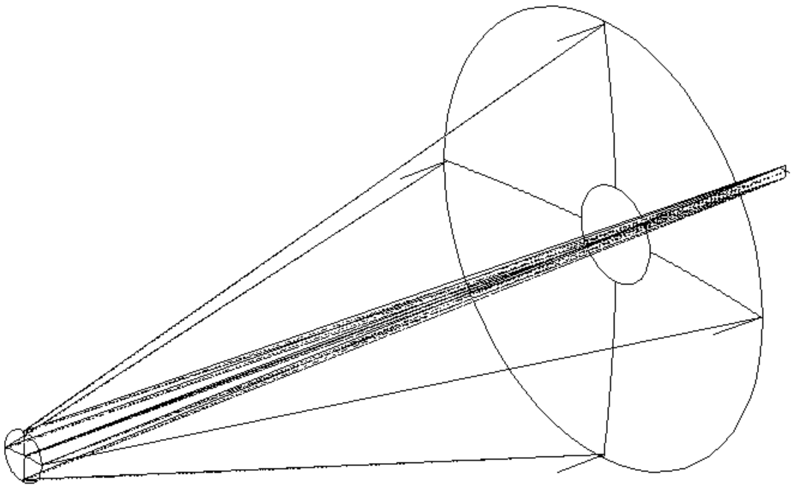
Integrated System Analysis - Example

Example: Telescope

Finite Element Model

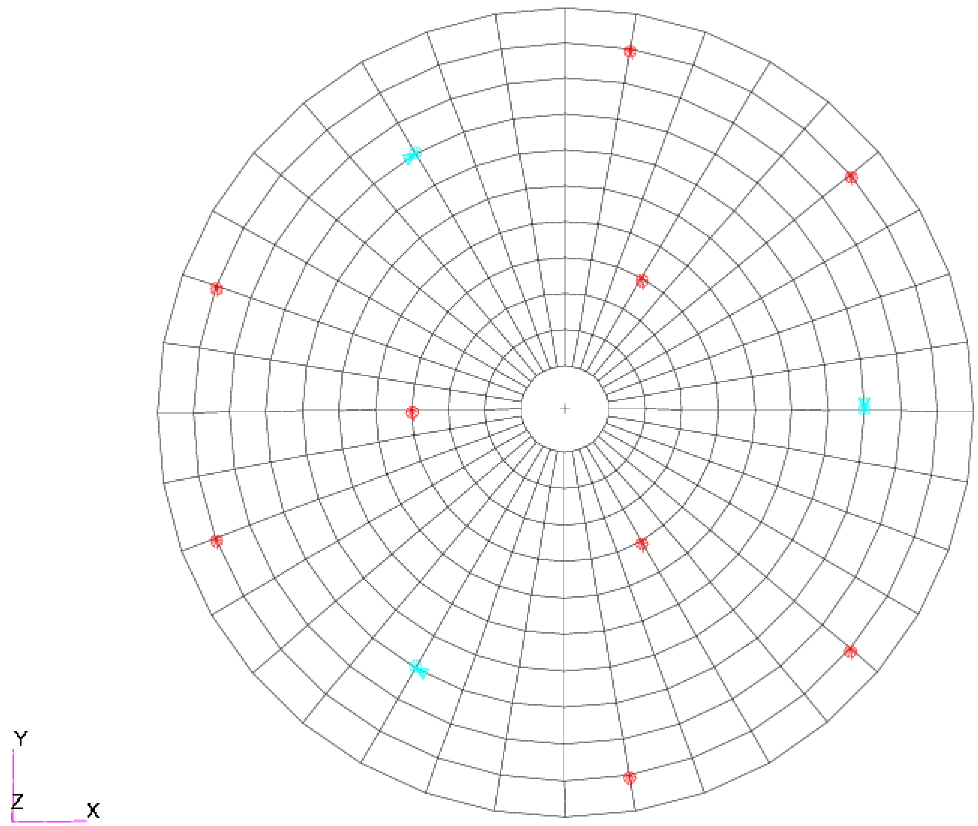


Optical Model



Integrated System Analysis - Example

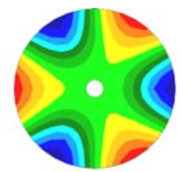
Adaptive PM (9 force actuators in red, 3 displacement actuators in blue)



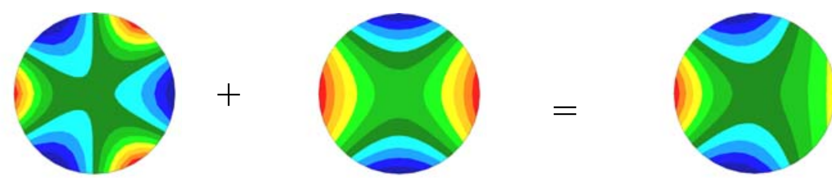
Integrated System Analysis - Example

- Load Case: 1g along optical axis
- Added 5λ of astigmatism on SM (represents a thermal distortion)

- PM sits on 3 points (displacement actuators)
  - 1g distortion = 4.62λ RMS
    - mostly trefoil = 12.5λ

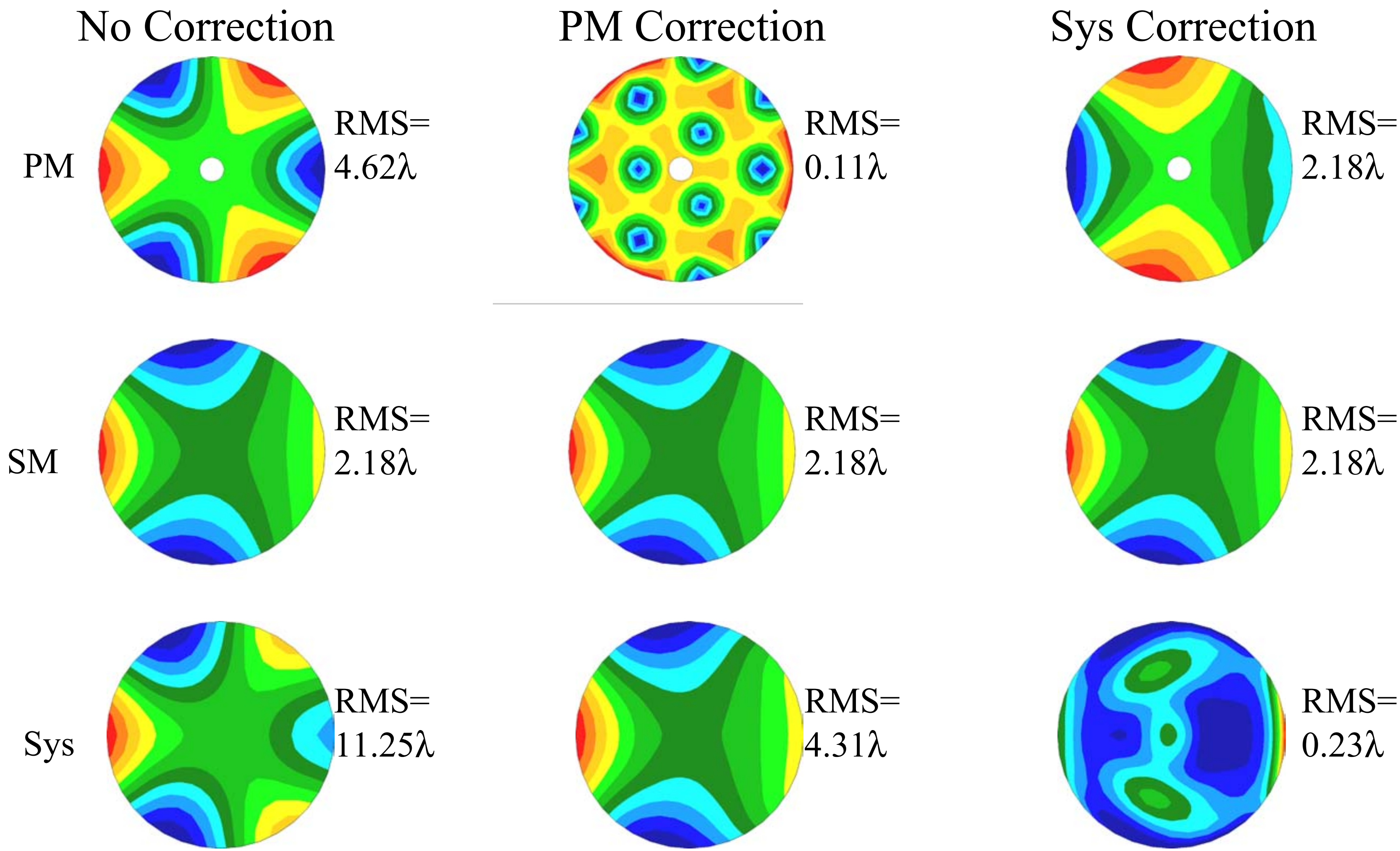


- SM sits on 3 edge points (with 5λ astigmatism added)
  - 1g distortion = 2.18λ RMS
    - trefoil = 2.0λ
    - added astigmatism = 5.0λ



- Note: Surface distortions have a doubling effect on reflected wavefront error

Integrated System Analysis - Example



Integrated System Analysis - Example

- Correcting PM disturbance only
  - Adaptive PM reduced PM error
  - Did not correct SM error, so SM effects still in System error

- Correcting System response
  - Adaptive PM corrected PM error and the SM error
  - Resulting System error greatly reduced

Integrated System Analysis -Example: Compare Sys Response with CodeV

ZFR	No-Corr Code-V	No-Corr SigFit	Corr'd Code-V	Corr'd SigFit	ZFR	No-Corr Code-V	No-Corr SigFit	Corr'd Code-V	Corr'd SigFit
2	-0.01	0.00	-0.01	0.00	21	0.00	0.00	-0.02	-0.02
3	0.00	0.00	0.00	0.00	22	0.00	0.00	0.00	0.00
4	-1.75	-1.75	0.01	0.00	23	0.00	0.00	-0.01	-0.01
5	9.91	9.91	0.04	0.04	24	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	25	-0.10	-0.10	0.11	0.11
7	0.00	0.00	0.24	0.24	26	0.00	0.00	0.09	0.09
8	0.00	0.00	0.00	0.00	27	0.00	0.00	0.00	0.00
9	1.85	1.85	0.00	0.00	28	0.00	0.00	0.01	0.01
10	-29.09	-29.10	0.00	0.00	29	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	30	-0.75	-0.76	0.22	0.22
12	-0.02	-0.02	0.57	0.57	31	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	32	0.00	0.00	0.01	0.01
14	0.00	0.00	-0.03	-0.03	33	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	34	0.00	0.00	0.00	0.00
16	-0.43	-0.43	0.00	0.00	35	0.00	0.00	0.00	0.00
17	0.00	0.00	0.16	0.16	36	-0.02	-0.02	-0.11	-0.11
18	0.00	0.00	0.00	0.00	37	0.10	0.10	0.07	0.07
19	5.18	5.19	-0.04	-0.04					
20	0.00	0.00	0.00	0.00	RMS	11.23	11.25	0.22	0.23

Summary

- SigFit's new System Level Analysis allows more rapid turn around of analyses
  - Optics engineer needed up front to get sensitivities
- Design and analysis under control of structural engineer
  - Can optimize on system level response
  - Reduces the need to budget each optic separately
- Improves and simplifies system level analyses
  - Can correct multiple surfaces' effects with single adaptive optic
  - Can combine multiple adaptive optics to correct system response
  - More accurate & useful than correcting a single surface's effect
- User features
  - Visualization plots of System Level Response
- Future development
  - Add System Level Response to SigFit dynamics
  - Add System Level Response to SigFit optimization equations for Nastran

References

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Genberg, V., Michels, G., "OptoMechanical Analysis of Segmented/Adaptive Optics", SPIE Paper 4444-10, August 2001.

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