Analysis to support
Advanced Mirror Design

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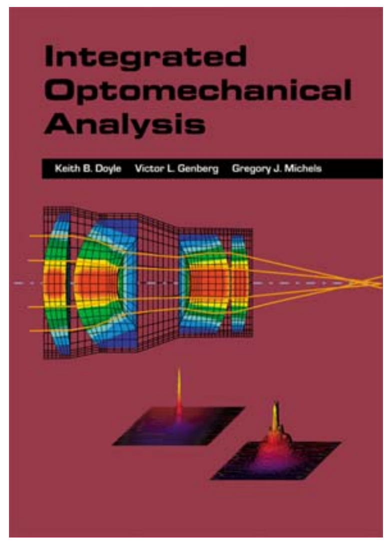
Outline

- Introduction

- Review Current capabilities/ New features/ Future plans
  - Surface fitting
  - Slumping
  - Adaptive
  - Tolerancing
  - Optmization

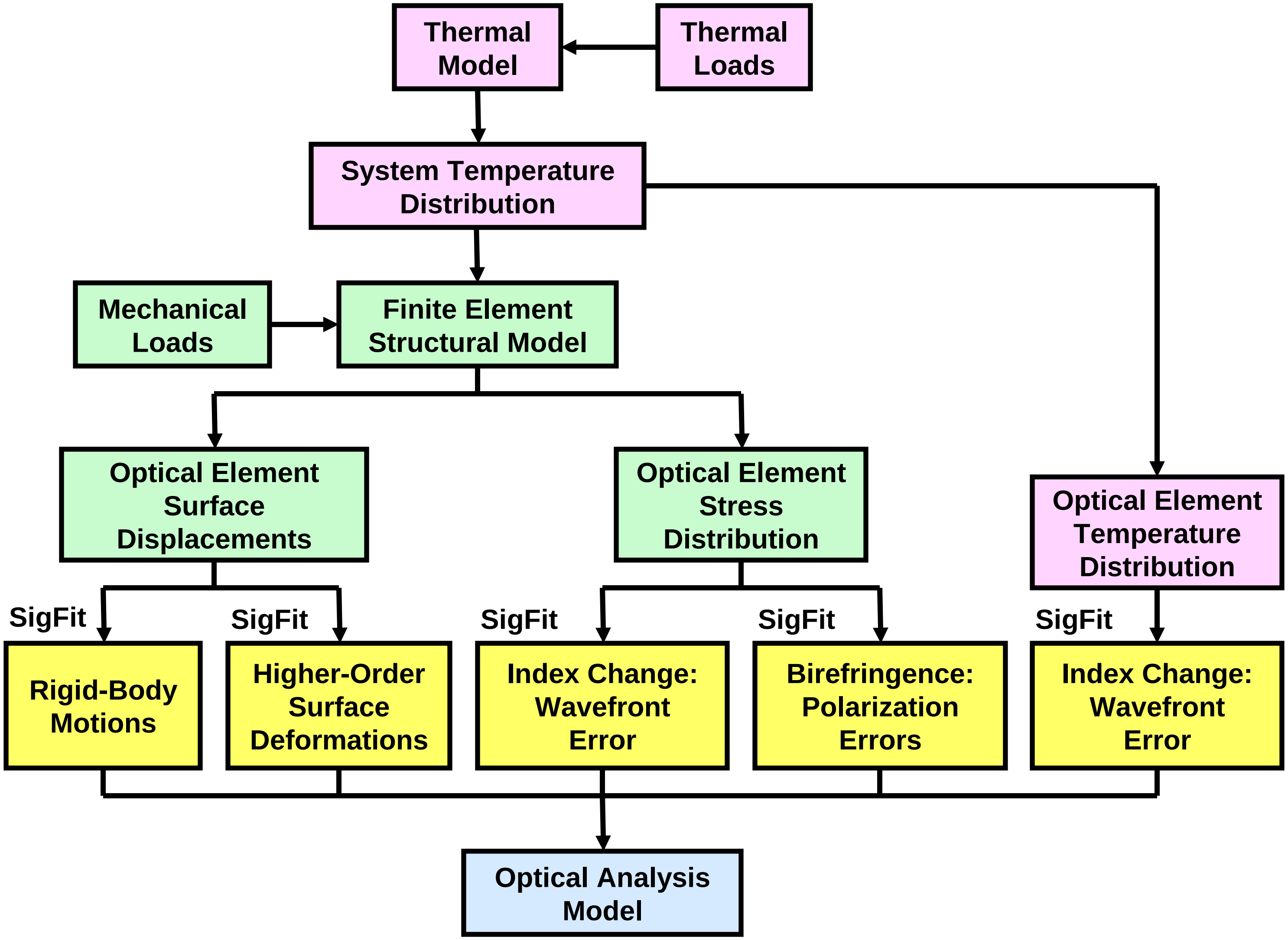
Sigmadyne, Inc. (Rochester, NY)

- Engineering Consultants in Integrated Optomechanical Analysis & Design
- Specializing in Optimum Design of Precision Optomechanical Systems
- Finite Element Analysis in support of Design, Fabrication, and Test
- Predict optomechanical performance over operational environment
- **SigFit** optomechanical analysis software
- Teach "Integrated Optomechanical Analysis" short course
- Authors: Integrated Optomechanical Analysis, SPIE Press, 2002

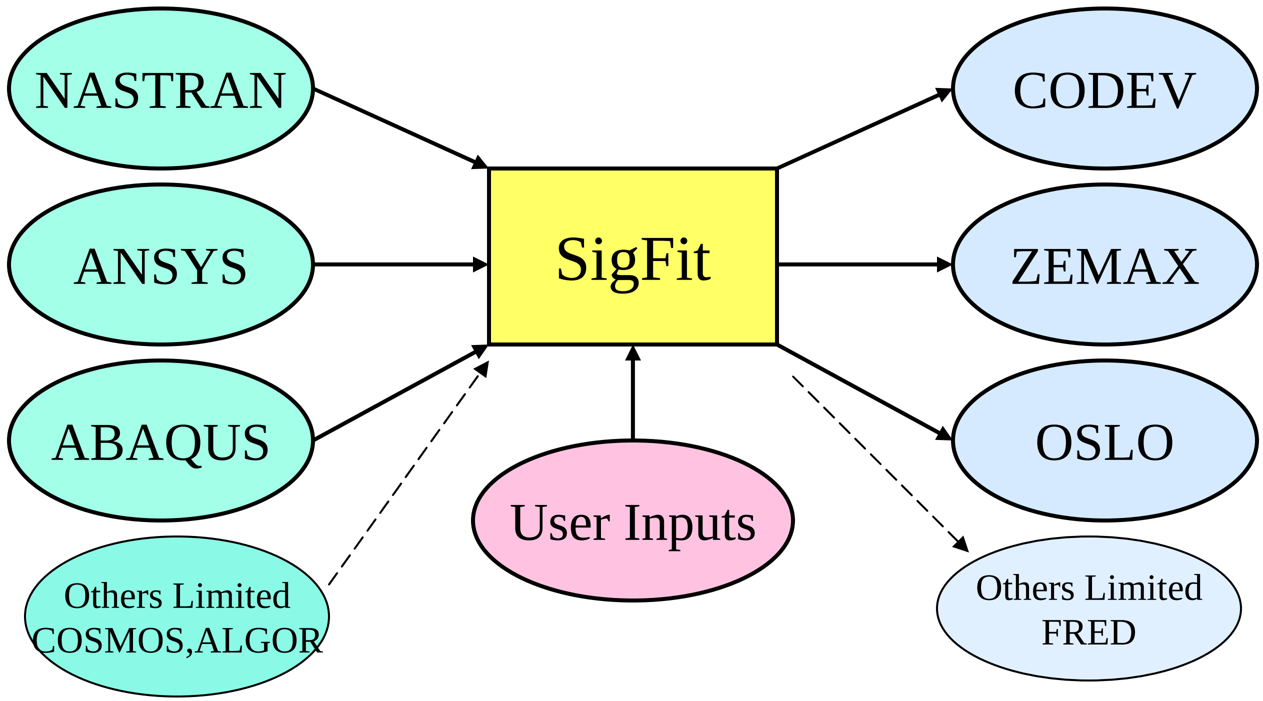


2nd edition
Aug 2012

SigFit introduction: Integrated Modeling Flow Chart



Current: Interfacing Multiple FEA Codes to Multiple Optical Codes



Finite Element Model Data
Node Locations
Element Connectivity
Coordinate Systems

Finite Element Model Results
Nodal Displacements
Nodal Temperatures
Element Stresses

Displacement Results
Rigid Body Motions
Normal Surface Deformations
Sag Surface Deformations

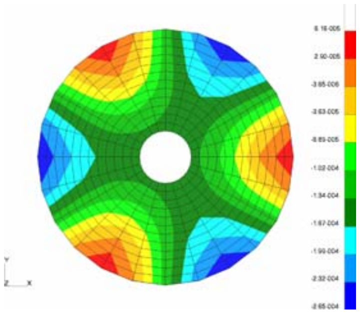
Optical Path Difference Results
OPD Maps

Birefringence Results
BIR and CAO Maps

Surface Fitting - Current

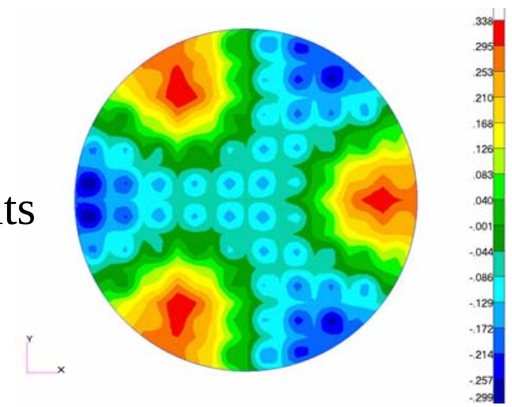
- Surface Fitting used to study mirror performance and optimize mirror design
  - in-use environments and test conditions (1-g backouts)

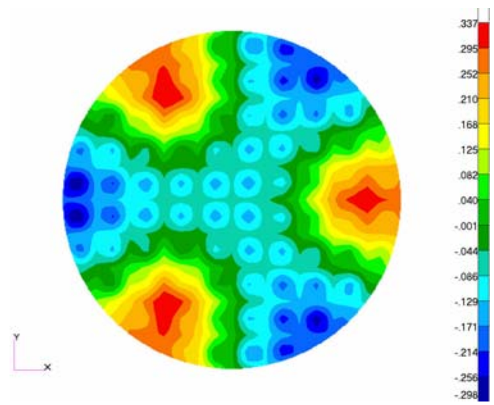
- Fit deformed shapes (FE results) with polynomials to pass to optics codes
  - Conventional: Zernikes (Standard & Fringe), Asphere, XY
    - Normalization and order to match optics code
  - X-ray: Fourier Legendre or Legendre in Z-Θ



- Interpolate to grid arrays if polynomials a poor fit

FE results





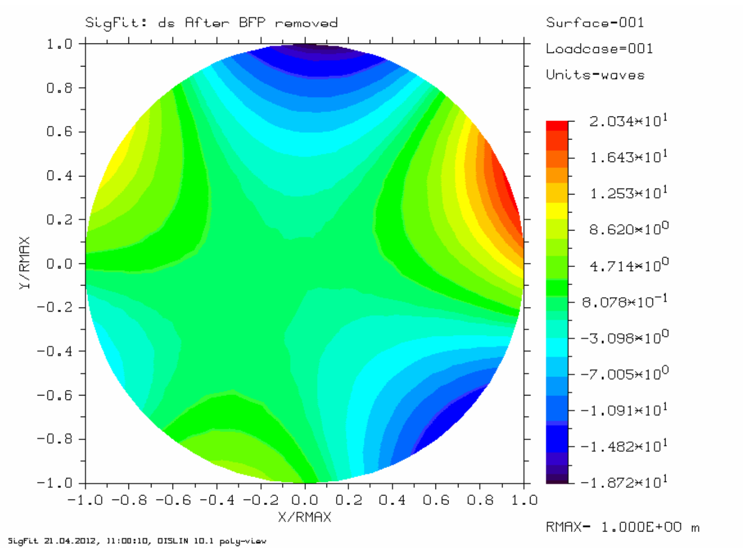
401 x 401 Array

Surface fitting – New and Future

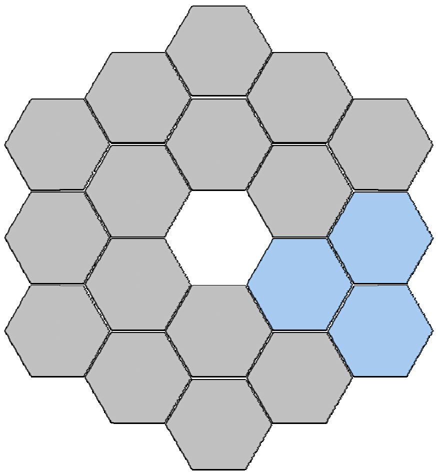
- New polynomial types: Forbes (QCON, QBFS)

- New contour plot output: png files (do NOT require FE PostProcessor)
  - Useful: for quick viewing of results

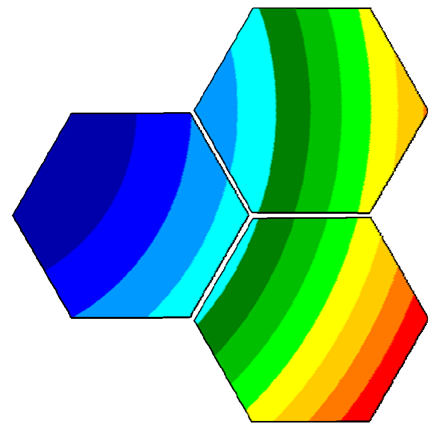
- Future I/F: SolidWorks and others



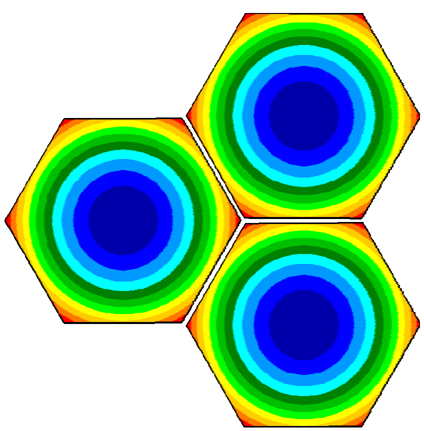
Slumping – off-axis segments



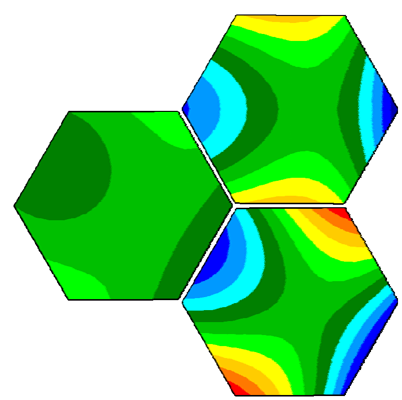
Segmented Mirror



Surface geometry based on assembly vertex (asphere)



Geometry in local segment system (Best-fit plane removed)



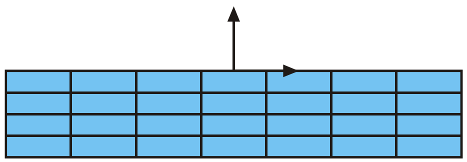
Geometry with power removed

Slumping – New features

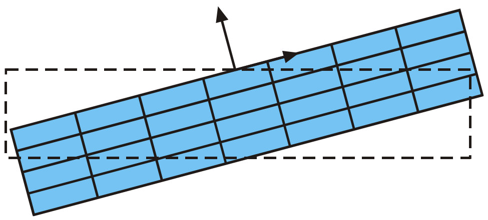
- Calculate Zernike fit
  - User input = RoC, Conic, Asphere and segment offset (X,Y)
  - SigFit calculates Zernikes in local segment system
  - Output Zernikes in CodeV/Zemax form
    - useful for polishing info
  - Write grid sag array if desired
  - Plots of surface shape in local system

- Slump FE model to correct geometry
  - create offset coord system (sag/normal)
  - drag existing coord sys and segment models
  - write corrected node position in FE format
    - important for thermoelastic loads

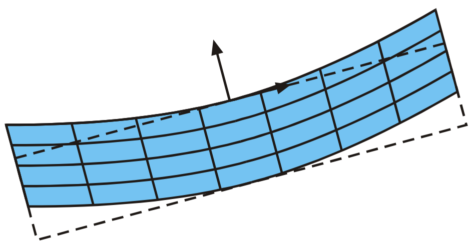
Slumping steps in SigFit (automated)



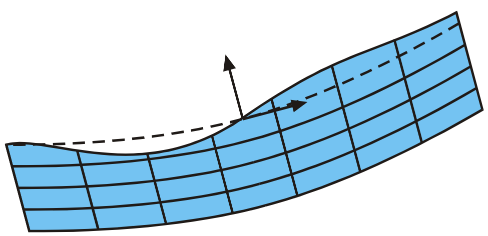
1) Create flat segment.



2) Specify offset distance (X, Y)
SigFit drags to correct position
and orientation.



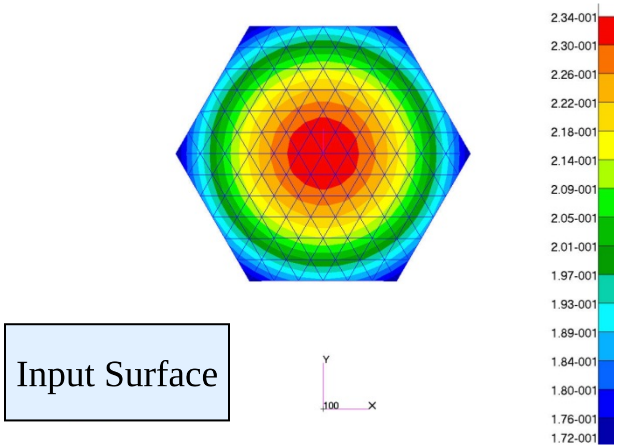
3) Slump full substrate to
best-fit radius.

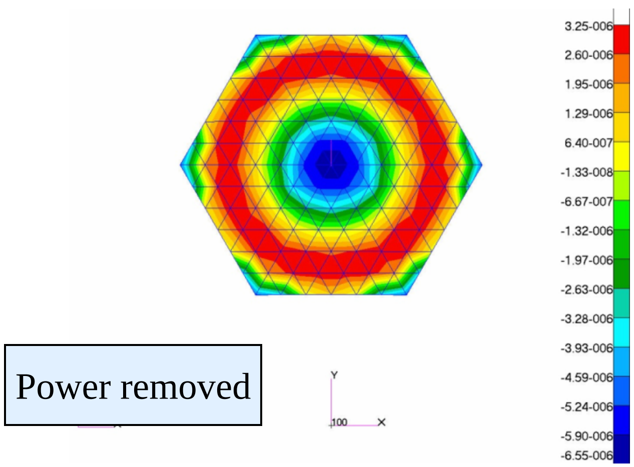


4) Slump optical face to
exact optical prescription.

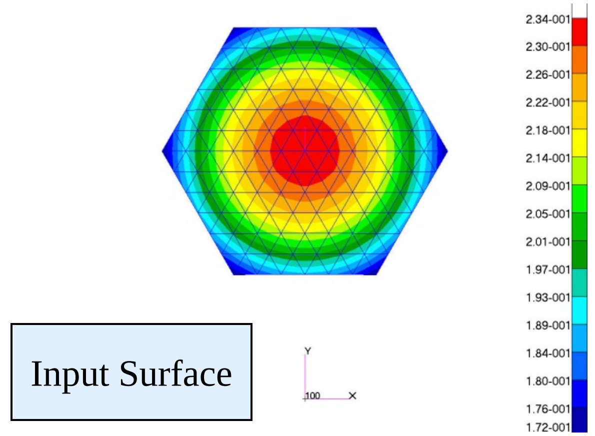
Thermoelastic distortion due to isothermal load

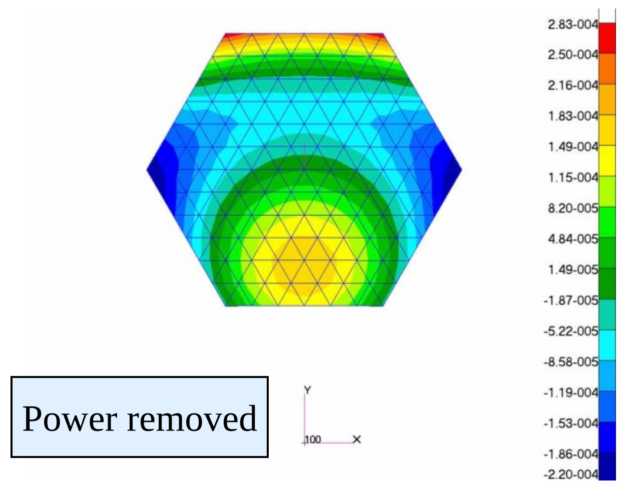
Mirror as Pure Sphere





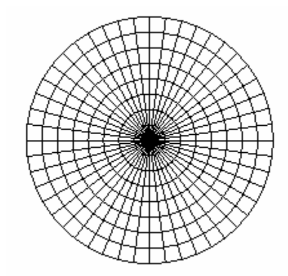
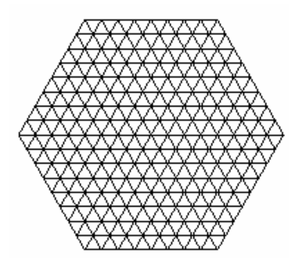
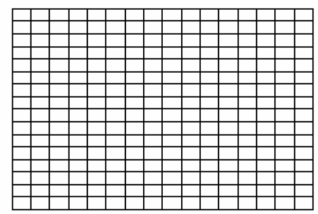
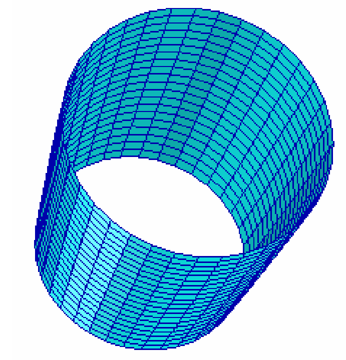
Surface Corrected to Asphere





MESH feature

- Create mesh of segments
  - shape, model detail

- Polynomial converter
  - polynomial types (asphere=> Zernike=>XY=etc)
  - amplitude normalization, radius normalization
  - aperture shape
  - linear combinations of polynomials
- Create plots and tables

Adaptive analysis – current features

- Useful for Adaptive optics, stressed-optic polishing, fitting test data
- Solve for actuator stroke (forces) to minimize surface RMS
- Write corrected surface to optics codes (polynomials or grid aray)
- Actuator stroke limits or force limits
- Actuator failure studies
- Actuator placement optimization (conventional optics)
  - SigFit has genetic optimization algorithm to select N best actuator locations
  - Best solution over multiple disturbance cases

SigFit adaptive analysis

Disturbance types

- FE model analysis cases
- Test interferogram arrays
- Polynomials and ΔRoC
- Vector data
- Linear combinations

Influence function types

- FE model analysis cases
- Test interferogram arrays
- Polynomials and ΔRoC
- Vector data
- Linear Combinations

Options

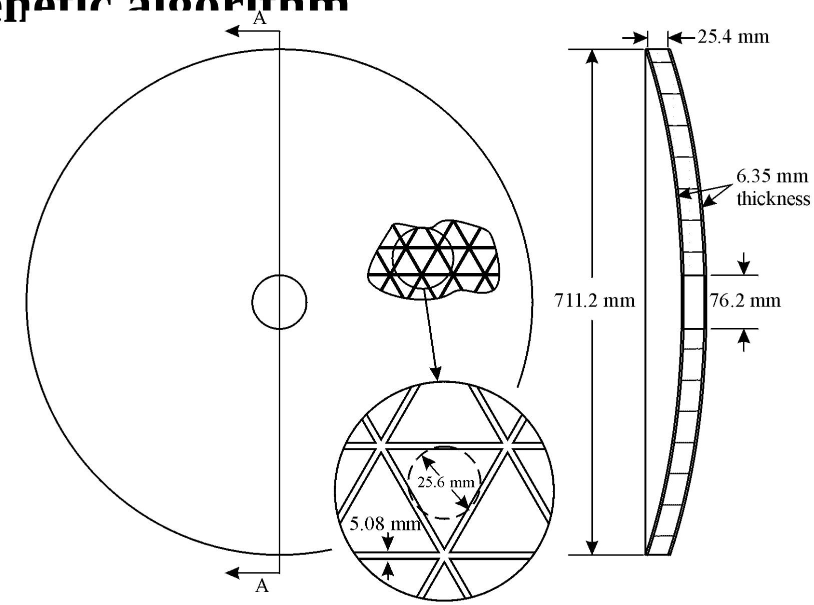
- Stroke limits
- Actuator failure
- Placement optimization
- Actuator resolution

→ Adaptive correction →

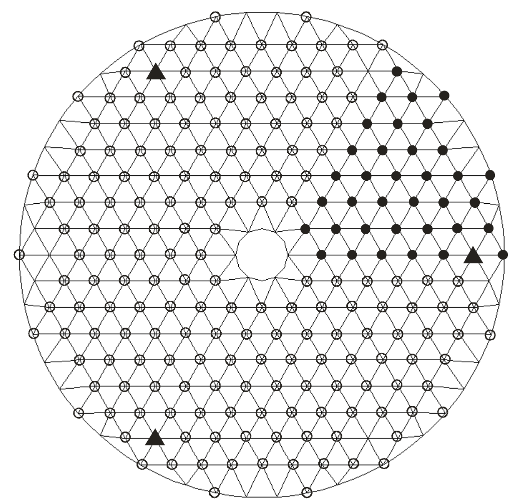
Results

- Correctability
- Actuator strokes
- Contour plots
- Surface polynomials
- Surface grid array
- Monte Carlo statistics

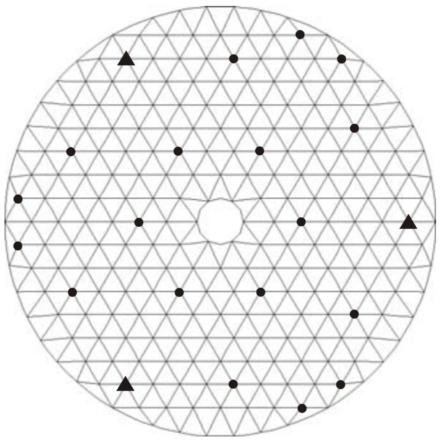
Actuator Placement Optimization using Genetic algorithm



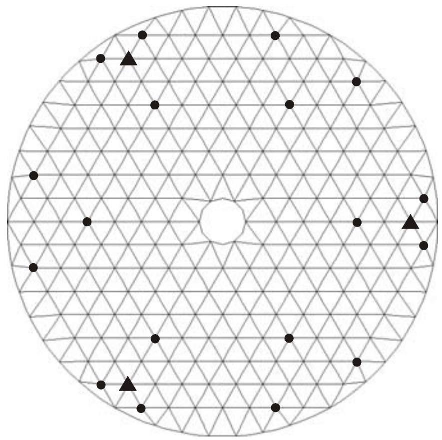
- Environmental disturbances
  - Gravity along optical axis
  - Isothermal 20C temperature drop
  - Front-to-back 0.15C temperature difference
  - Combine all of the above
- Candidate actuators
  - 210 candidate actuator locations
  - 35 master locations for six-fold symmetry
  - 3 fixed location displacement actuators
- Objective
  - Find best layout of 18 actuators
  - 6545 possible layouts of 18 actuators each



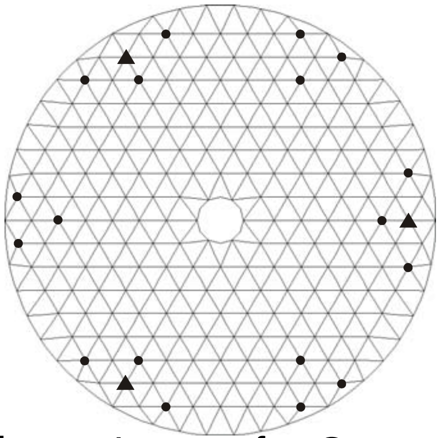
Example - Optimum Actuator Layouts



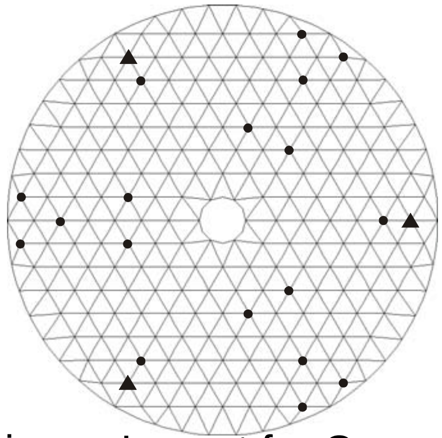
Optimum Layout for Correction
of Gravity Loading



Optimum Layout for Correction
of Isothermal Temperature Changes



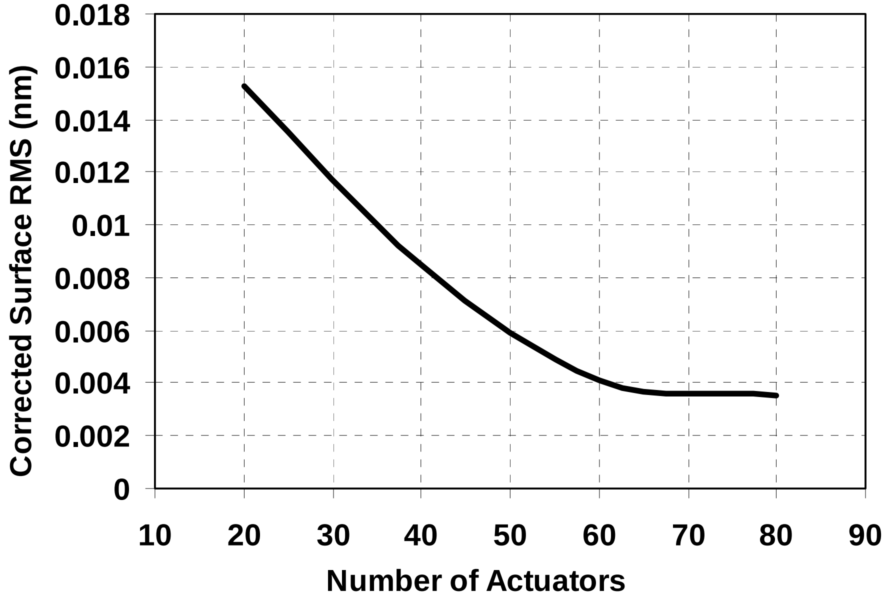
Optimum Layout for Correction
of Axial Thermal Gradient

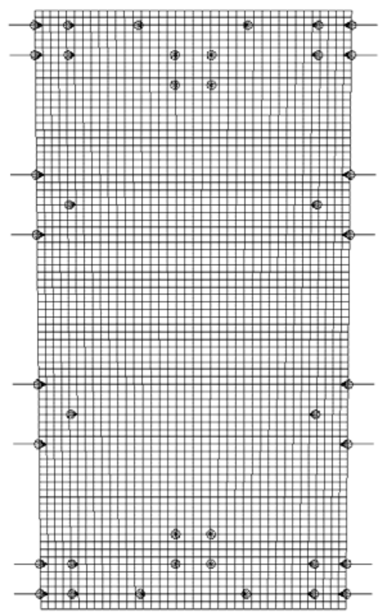


Optimum Layout for Correction
of Combined Loading

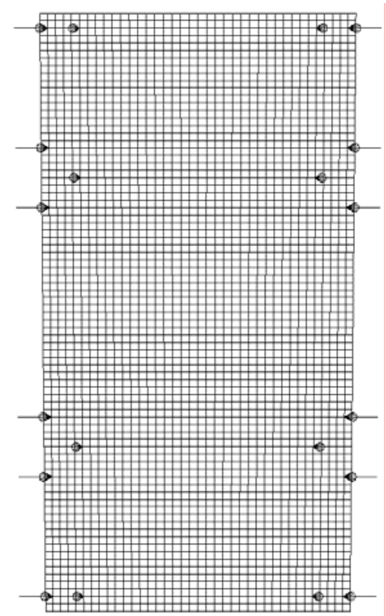
New Adaptive: Actuator Layout Optimization example for X-Ray optics

- Load cases: axial thermal gradient <u>and</u> circumferential thermal gradient
- Successive optimizations generate a design curve of corrected performance vs. number of actuators



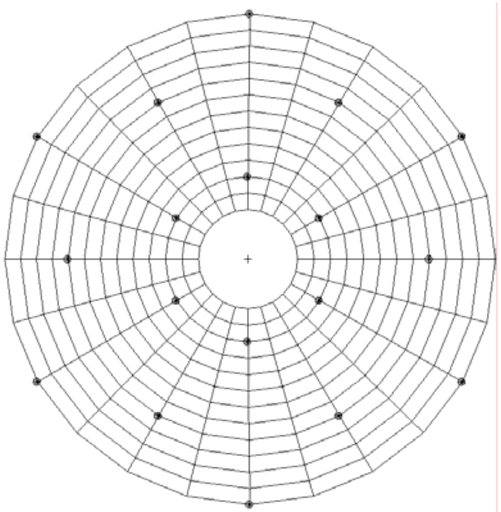


Optimum 40-Actuator Layout

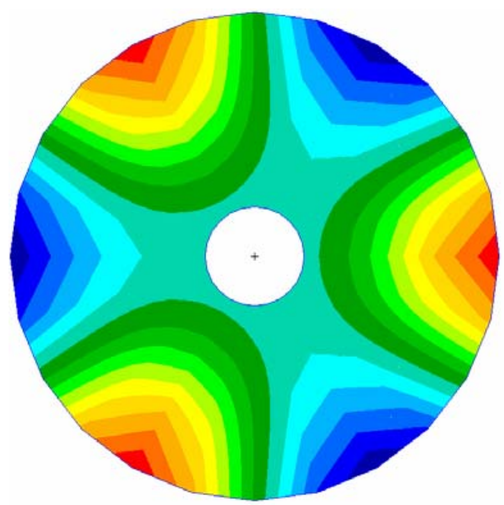


Optimum 20-Actuator Layout

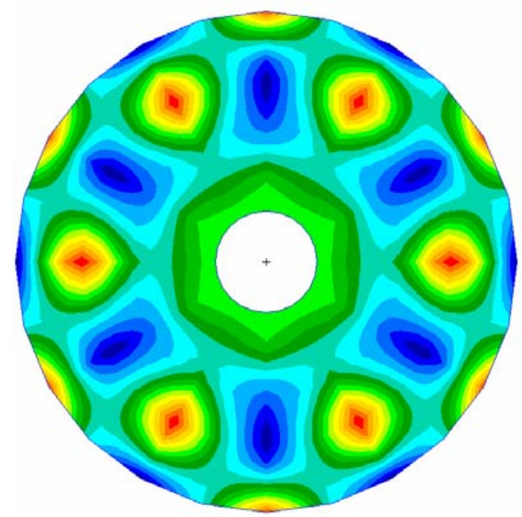
New Adaptive: Actuator resolution for adaptive optic (via Monte Carlo)



Mirror on 3 point mount
3 displacement actuators
15 force actuators



Sag in 1g on 3 points
RMS = 3.0 λ (after best-fit-plane subtracted)

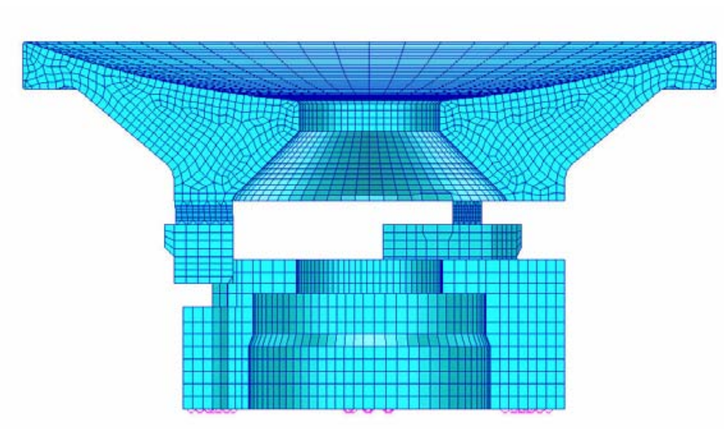


Adaptively corrected
RMS = 0.052 λ
(Perfect actuators)
(98% correctable)

Using ‘perfect’ actuators, corrected surface = **0.052 λ**

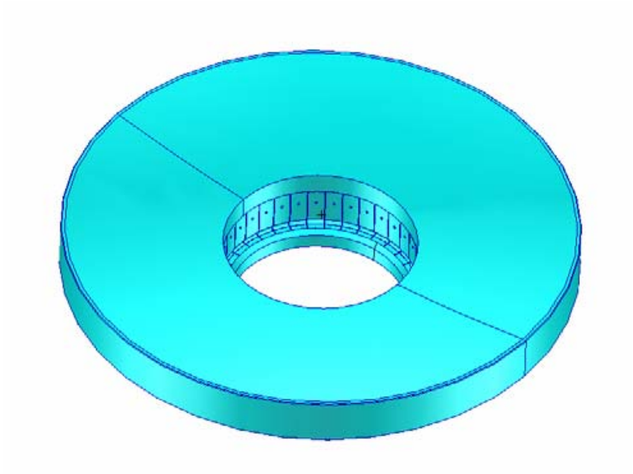
If actuators had a 1% variablity, corrected surface = **0.079 λ** for 95% confidence
Using SigFit’s Monte Carlo analysis with 1000 random variations.

Adaptive analysis – as design tool



eNi coating required on front face.
To counteract thermoelastic effect –
where and how thick eNi on back surfaces

Use adaptive analysis to size coating thickness
(each zone local coating effect = adaptive subcase)



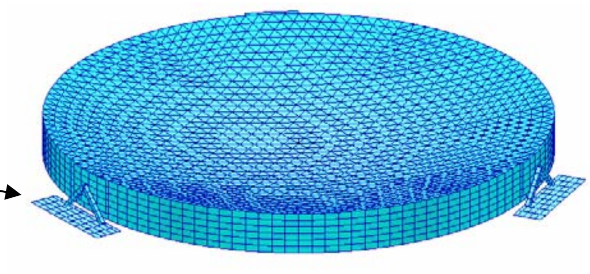
Mirror tested with inner hub bolted to a test plate fixture at 6 points.

Measured surface error (astigmatism) was unexplained.

Use adaptive to show mounting fixture non-flatness is cause of distortion.
(each bolt unit distortion = adaptive subcase)

New Tolerancing capability

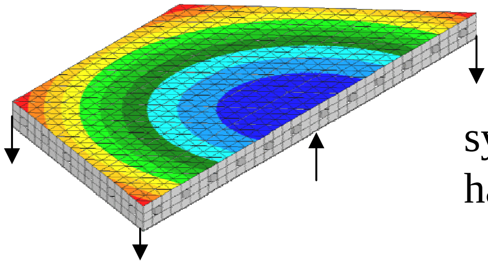
- Monte Carlo techniques to create tolerances based on optical performance
  - Each quantity treated as random variable with distribution
  - User specifies number analyses and confidence level
  - SigFit calculates variations of BFP, polynomials, surface RMS, LoS
- Mount flatness requirements
  - flatness and coplanarity



Mirror on flexures bolted to support structure

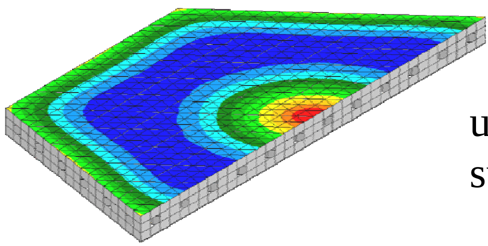
- Other examples
  - Substrate CTE variation
  - Coating thickness variation
  - Actuator resolution

Mirror optimization - current features



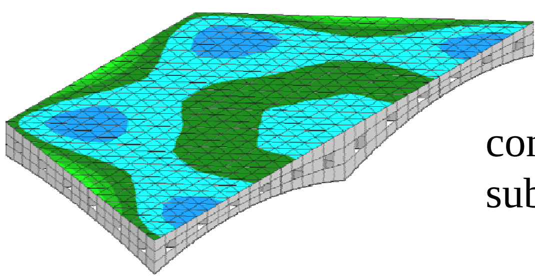
symmetric
half model

Adaptive mirror thermal distortion



uniform
substrate

Adaptively corrected surface error



contoured
substrate

Optimized design (3x improvement)

SigFit writes optical performance
measures as FE model input data
for use as design objective
or as design constraints

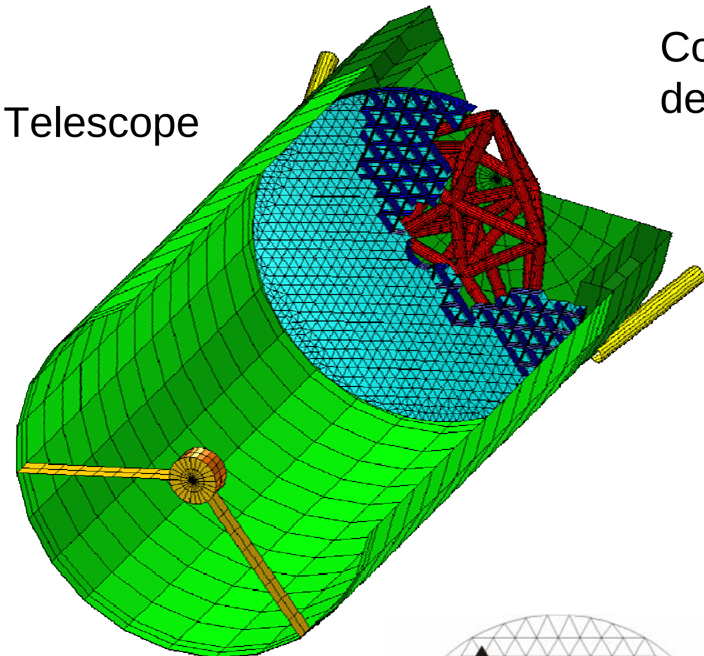
Polynomial coefficients

Surface error (RMS and P-V)
with BFP and polynomials removed

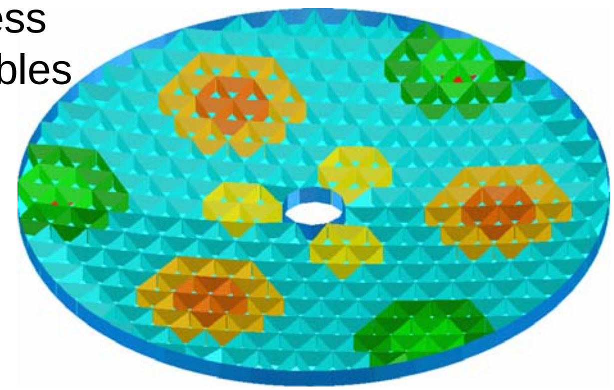
Line-of-sight equations

NEW Optimization - System Level WFE performance constraints

Telescope

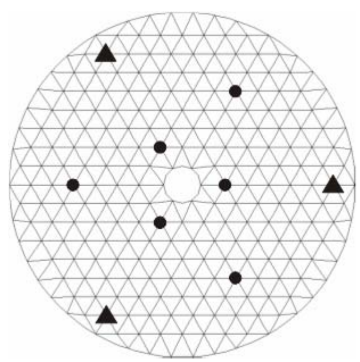


Core thickness design variables



Adaptive Primary Mirror

Actuator locations



linear optics model with Nastran's DRESP3 call to SigFit

Response	Initial Design	Optimized Design	Requirement
Thermally Induced Wavefront Error	9 nm	20 nm	20 nm
Gravity Release Induced Wavefront Error	54 nm	60 nm	60 nm
Peak Launch Stresses	1000 psi	1000 psi	1000 psi
First Natural Frequency	231 Hz	221 Hz	200 Hz
Weight	20.8 kg	9.9 kg	Minimum
Areal Density	53.0 kg/m^2	25.2 kg/m^2	Minimum

Optimized Primary Mirror Summary
Weight cut by 1/2

Other new features

- New capabilities in system analysis
  - LoS analyses, new output file options
    - LoS X,Y contibution by mode, contribution by surface
  - MTF calculation due to jitter
    - random & harmonic

- Thermo-optic analysis for refractive optics
  - New gradient index interface for better accuracy

- Aero-optic analysis
  - New capability for optical effects of air density variation
  - I/F to CFD results

Summary – analysis to support mirror design.

- Analysis tools for mirrors facilitate the
  - design, optimization, fabrication, testing

- Current capabilities/ New features/ Future plans
  - Surface fitting, Slumping, Adaptive, Tolerancing, Optmization

- Our papers are available from our website:
  - **www.sigmadyne.com**
  - Click on **publications** button to download (approx 30)