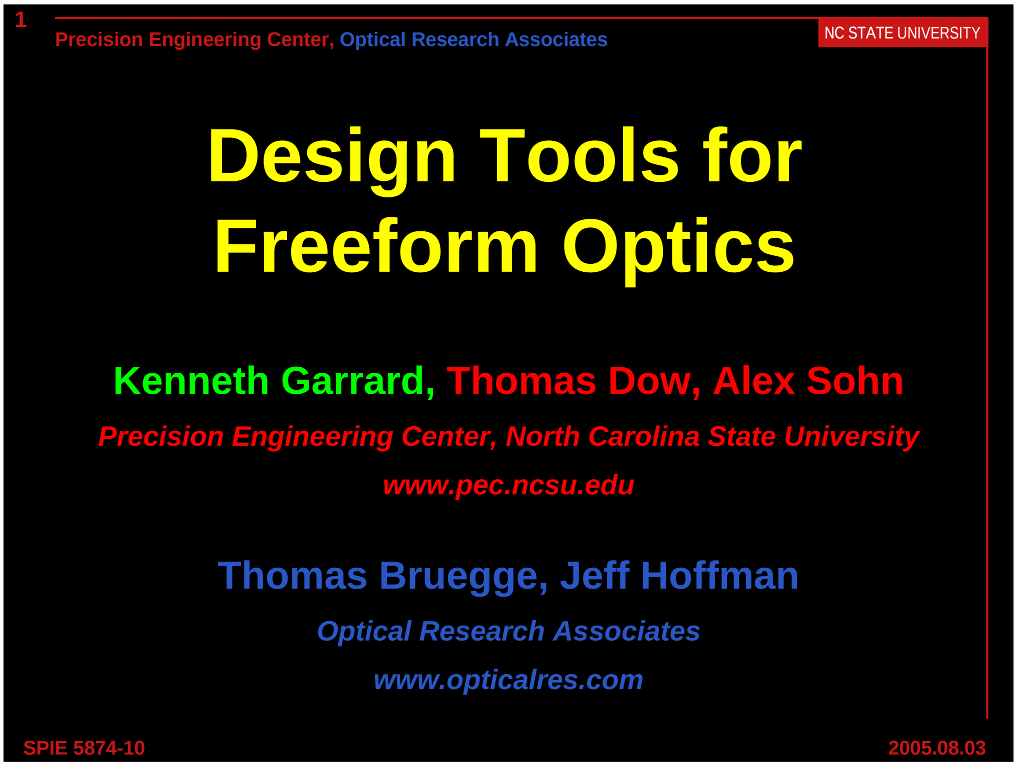

Design Tools for Freeform Optics

Kenneth Garrard, Thomas Dow, Alex Sohn
Precision Engineering Center, North Carolina State University
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Thomas Bruegge, Jeff Hoffman
Optical Research Associates
www.opticalres.com

SPIE 5874-10 2005.08.03

The inclusion of freeform elements in an optical system provide opportunities for numerous improvements in performance. However, designers are reluctant to utilize freeform surfaces due to the complexity and uncertainty of their fabrication. An enhanced design environment is needed to move freeform surfaces into the mainstream; one that gives the designer feedback on the manufacturability of the design as well as its optical performance. This environment needs a fundamentally new figure of merit to simultaneously predict optical performance and fabrication complexity. The kernel of this design environment has been incorporated in the CODE V design software for a limited class of surfaces.

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Acknowledgements

US Army

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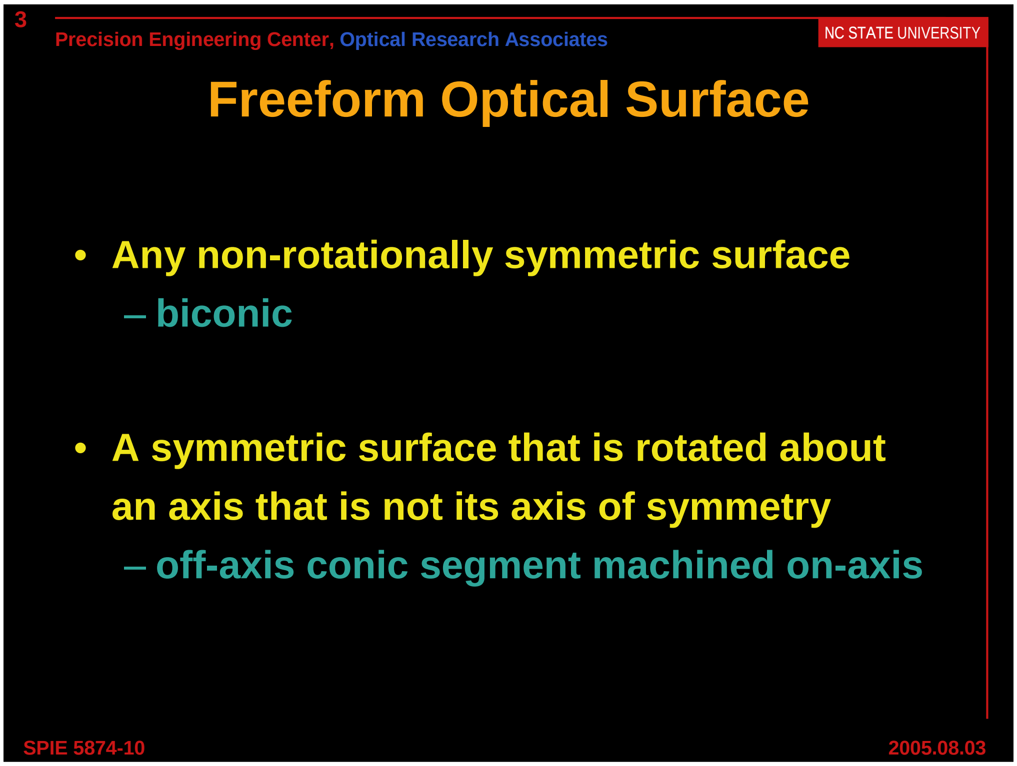

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Freeform Optical Surface

- Any non-rotationally symmetric surface
  - biconic
- A symmetric surface that is rotated about an axis that is not its axis of symmetry
  - off-axis conic segment machined on-axis

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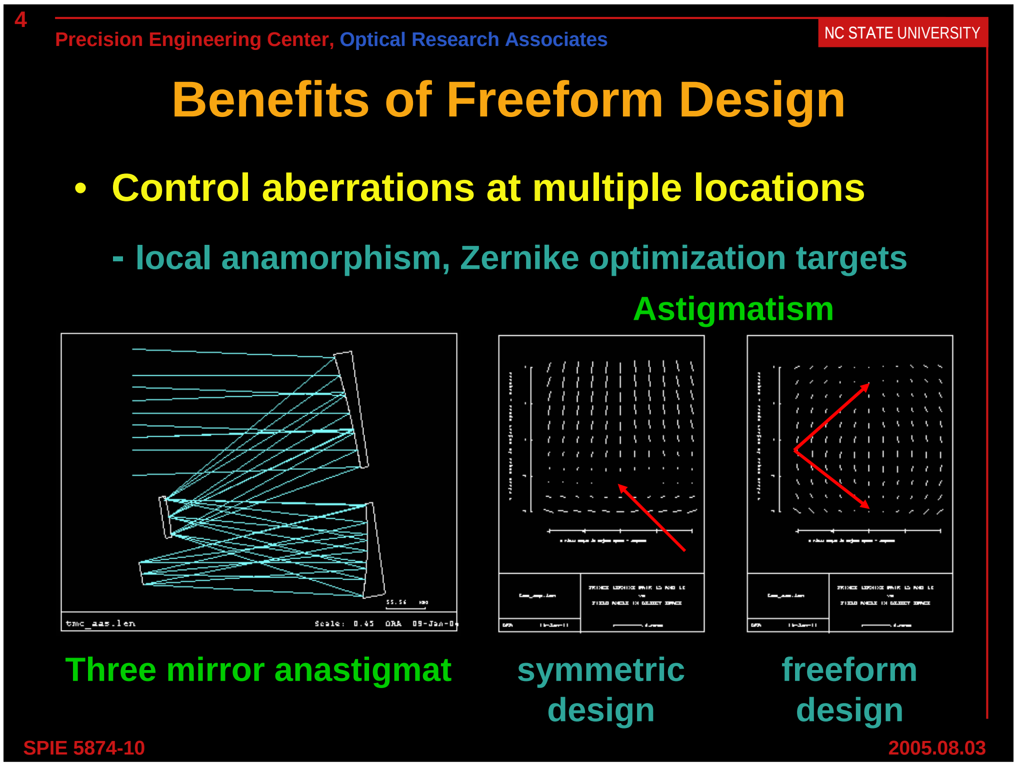

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Benefits of Freeform Design

- Control aberrations at multiple locations
  - local anamorphism, Zernike optimization targets

Astigmatism

Three mirror anastigmat

symmetric design

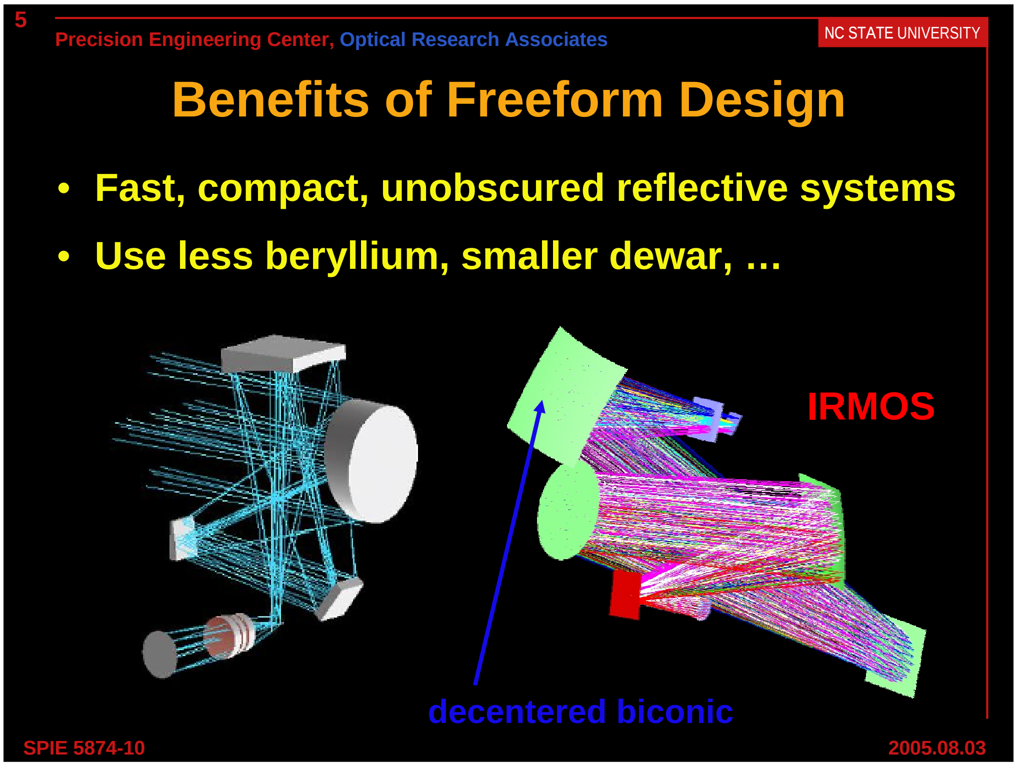
freeform design

SPIE 5874-10

2005.08.03

- Three mirror anastigmat – correction of spherical aberration, coma and astigmatism

- Control of astigmatism at multiple field points
- Reduce total wavefront error
- Optimize on constraining Zernike coefficients for astigmatism



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Benefits of Freeform Design

- Fast, compact, unobscured reflective systems
- Use less beryllium, smaller dewar, …

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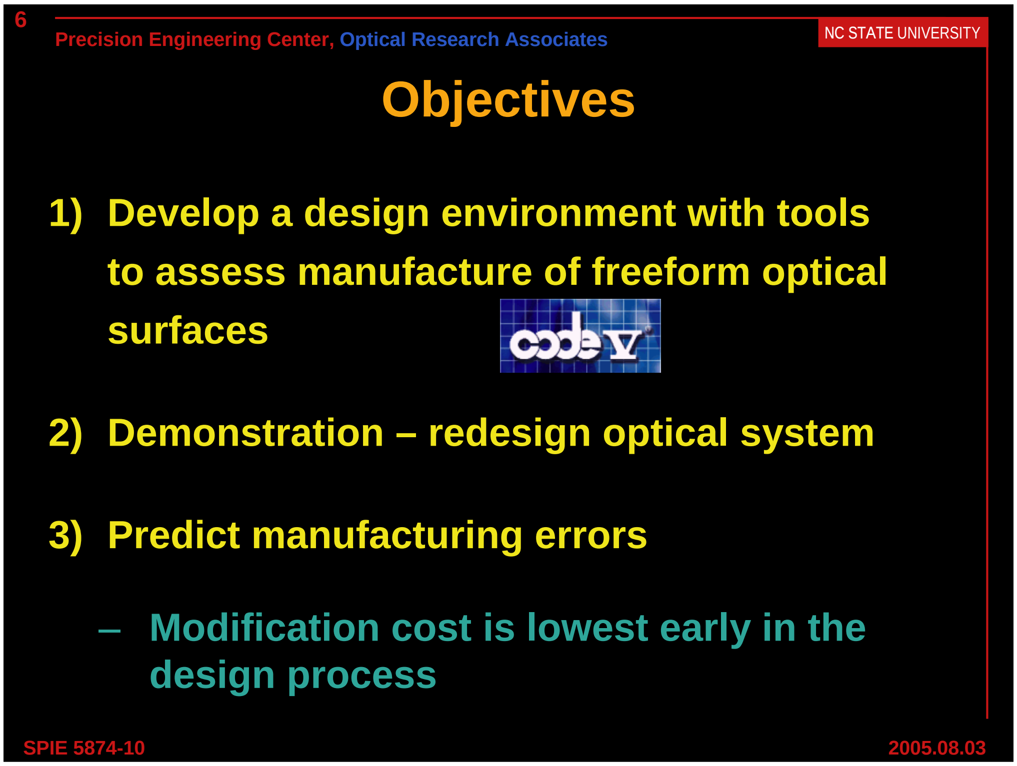
- Fast optics, compact packaging

- Infared Multiple Object Spectrometer is shown on the right
- The PEC was approached by NASA/Goddard to machine M4, an off-axis biconic ellipsoid – no axis of rotational symmetry
- Design modification was offered as alternative to simplify fabrication

- Shouldn’t this have been part of the design software ?
- This project provided the impetus to modify optical design software to include feedback on cost of manufacture and predict errors in fabrication processes



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Objectives

1) Develop a design environment with tools to assess manufacture of freeform optical surfaces
2) Demonstration – redesign optical system
3) Predict manufacturing errors
   - Modification cost is lowest early in the design process

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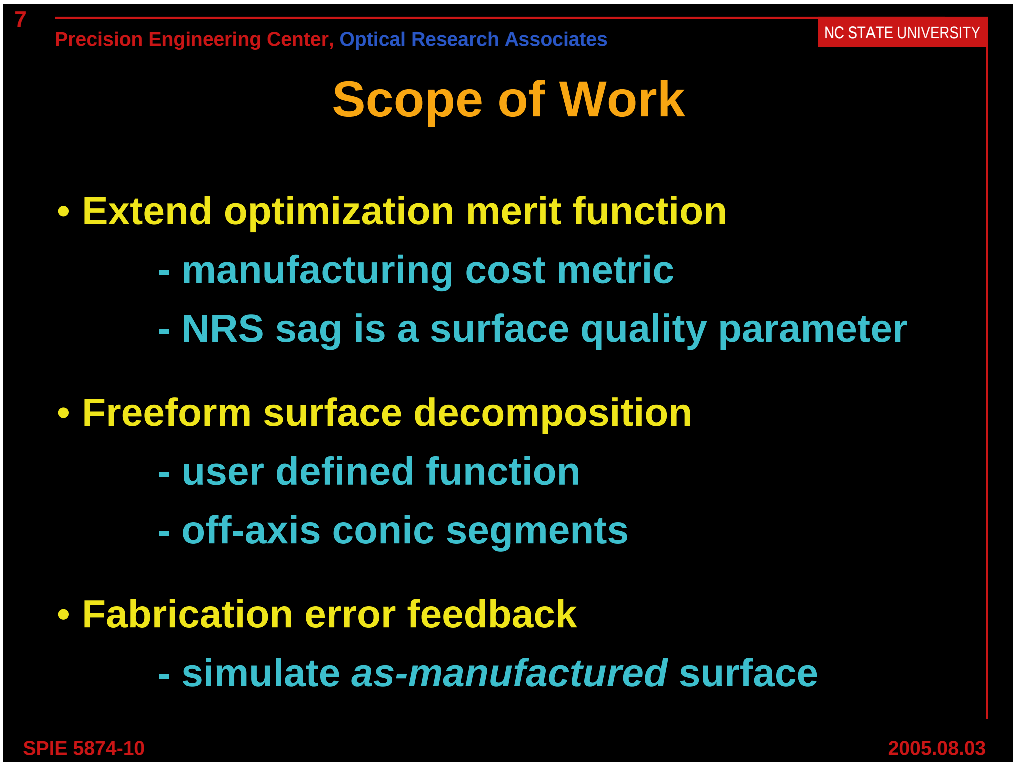
By decomposing a freeform surface into an axially symmetric surface plus non-rotationally symmetric deformations, the complexity and cost of manufacture can be estimated. This estimate can be weighted and used in the optimization merit function. Furthermore, a mechanism for predicting the results of the manufacturing process has been developed that can be fed back into the optical design environment to simulate the as-built optical performance.

For the first time, both traditional optical performance measures and new manufacturing specific process metrics can be simultaneously optimized. Coupled with existing commercially available optical design capabilities, this new software enables optical system designers to deploy cost effective freeform surfaces.



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Scope of Work

- **Extend optimization merit function**
    - **manufacturing cost metric**
    - **NRS sag is a surface quality parameter**
- **Freeform surface decomposition**
    - **user defined function**
    - **off-axis conic segments**
- **Fabrication error feedback**
    - **simulate *as-manufactured* surface**

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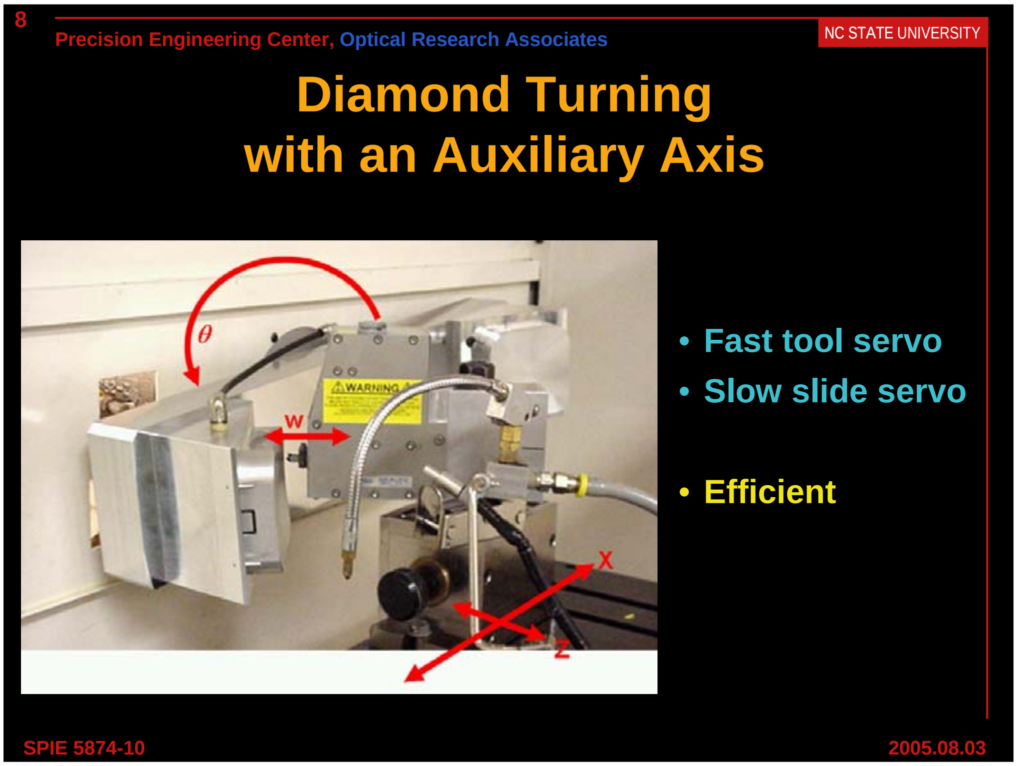

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Diamond Turning with an Auxiliary Axis

- Fast tool servo
- Slow slide servo
- Efficient

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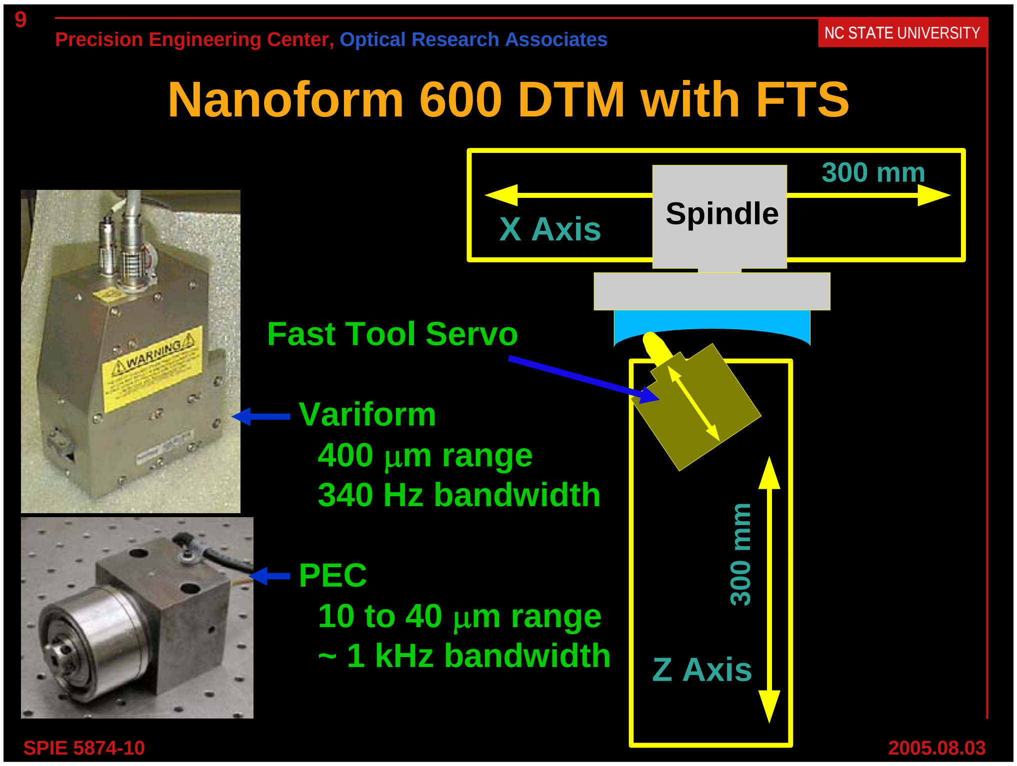
- Efficient machining, on-axis duty cycle is 100%
- Mature technology with many years of experience at the Precision Engineering Center

- Photo shows the IRMOS M4 blanks on a Nanoform 600 Diamond Turning Machine

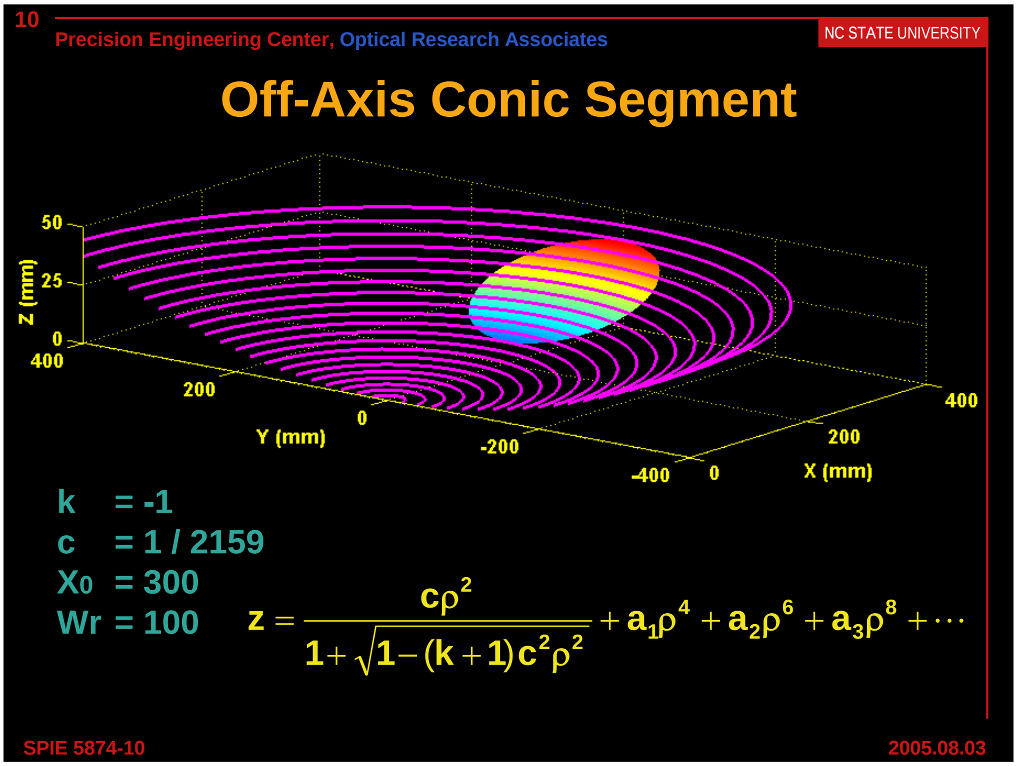


Nanoform 600 DTM with FTS

Fast Tool Servo

Variform
400 µm range
340 Hz bandwidth

PEC
10 to 40 µm range
~ 1 kHz bandwidth



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Off-Axis Conic Segment

k = -1
c = 1 / 2159
X_0 = 300
Wr = 100

$$z = \frac{c\rho^2}{1+\sqrt{1-(k+1)c^2\rho^2}} + a_1\rho^4 + a_2\rho^6 + a_3\rho^8 + \cdots$$

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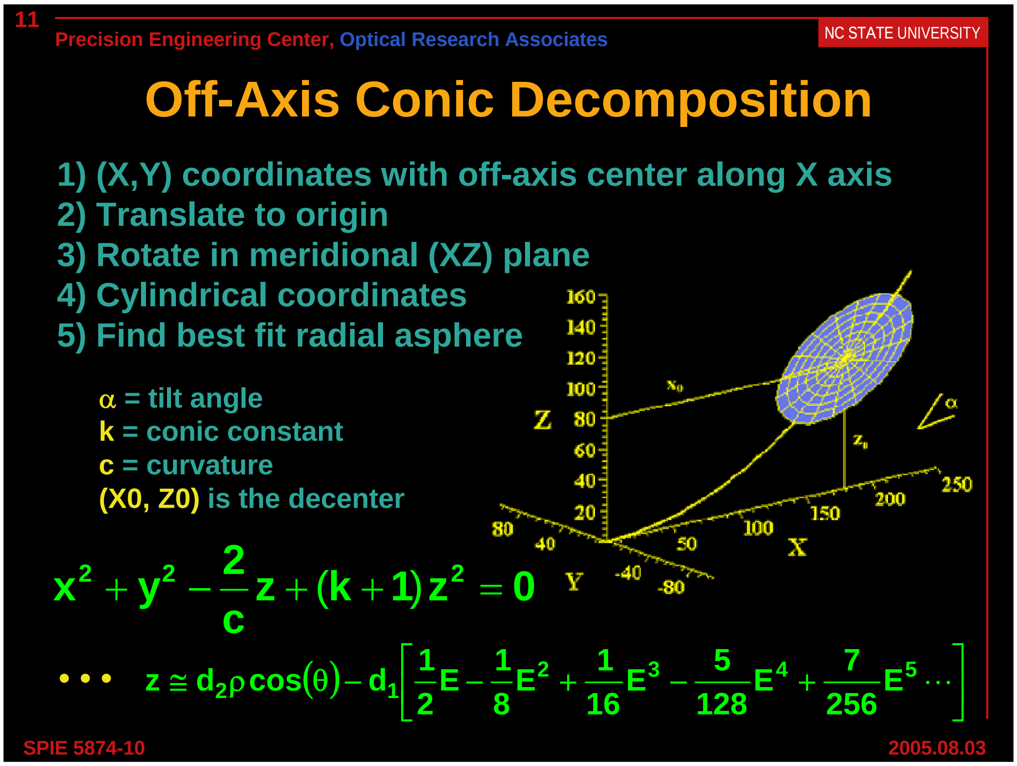
- Off-axis segment fabrication for any conic surface of revolution
- Example segment (shaded figure) is a large radius paraboloid
  Wr is the aperture radius
  X_0 is the distance from the center to the origin

- Described by the “optics equation” with curvature at the vertex (c) and conic constant (k) parameters,
  k = 0 (sphere)
  k = -1 (paraboloid)
  k < -1 (hyperboloid)
  k > 0 (oblate ellipsoid, rotate about minor axis)
  -1 < k < 0 (prolate ellipsoid, rotate about major axis)



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Off-Axis Conic Decomposition

1) (X,Y) coordinates with off-axis center along X axis
2) Translate to origin
3) Rotate in meridional (XZ) plane
4) Cylindrical coordinates
5) Find best fit radial asphere

α = tilt angle
k = conic constant
c = curvature
(X0, Z0) is the decenter

$$x^2 + y^2 - \frac{2}{c} z + (k+1) z^2 = 0$$

• • • $z \cong d_2 \rho \cos(\theta) - d_1 \left[\frac{1}{2}E - \frac{1}{8}E^2 + \frac{1}{16}E^3 - \frac{5}{128}E^4 + \frac{7}{256}E^5 \cdots \right]$

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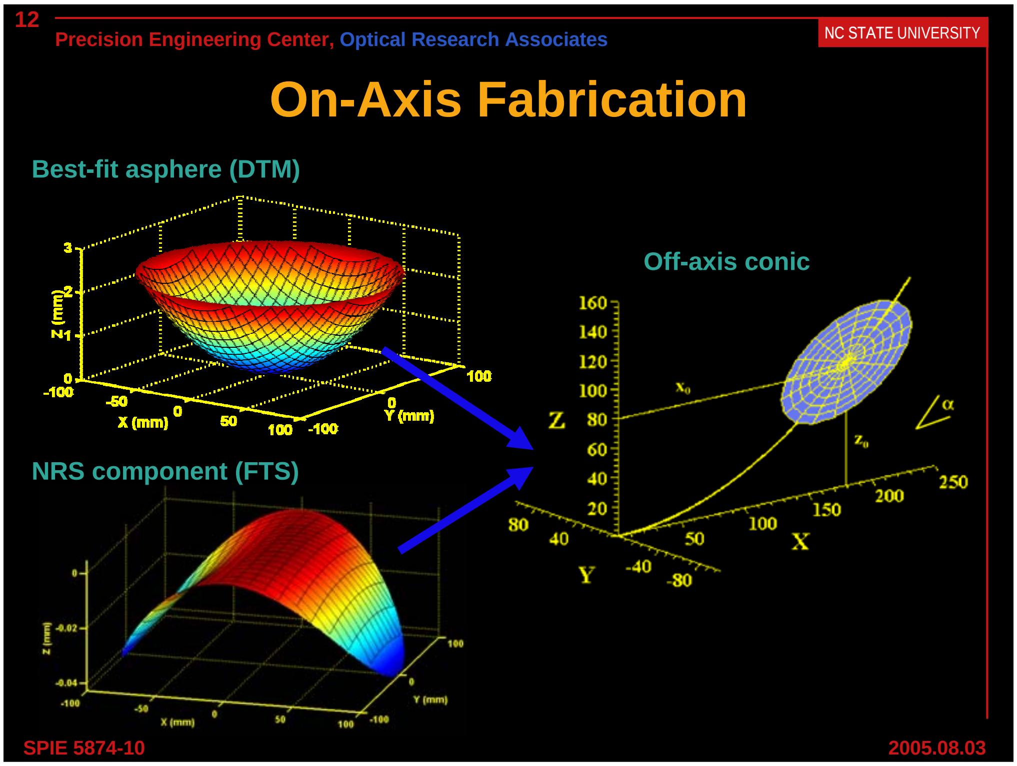
- Implicit form of optics equation is used
- Automatic decomposition process
- Considerable simplification to get to final equation
- d1, d2 and E are constants that depend on tilt, decenter, conic constant and curvature
- Possible to swap order of steps 3 and 4 and use a parametric form of the general optics equation
- Result is much simpler and can be generalized to any parametric surface

- See references in proceedings paper: Thompson, Gerchman, Garrard



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On-Axis Fabrication

Best-fit asphere (DTM)

Off-axis conic

NRS component (FTS)

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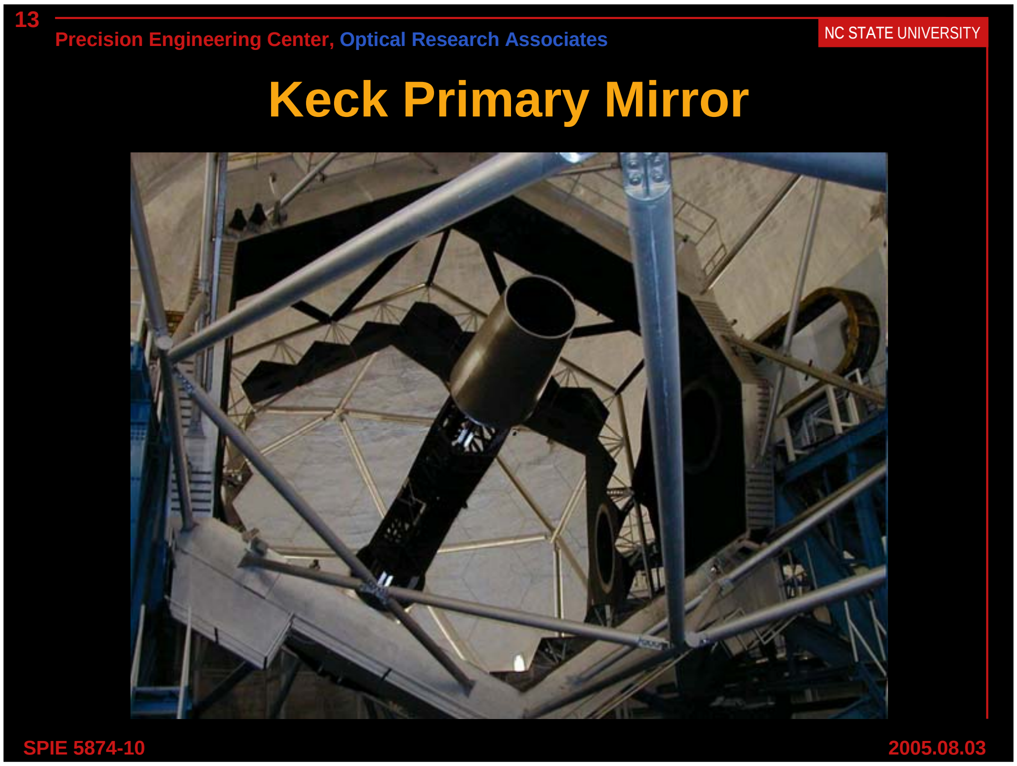
- Resulting “best-fit” asphere that minimizes residual FTS excursion
- NRS component is automatically generated by software for off-axis conics machined on-axis
- Asphere and NRS surface must be machined simultaneously with perfect synchronization to “add-up” to the desired off-axis conic

- Note factor of 100x for Z axis in NRS plot vs asphere plot



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Keck Primary Mirror

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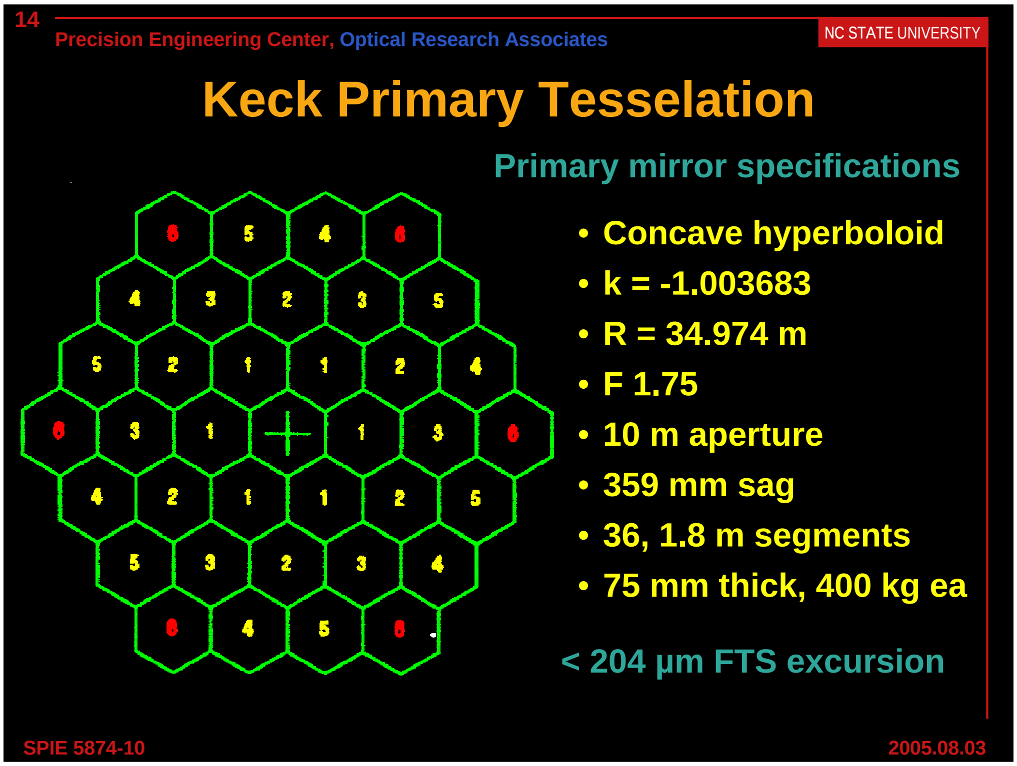
- To demonstrate the effectiveness of the decomposition process consider the segemented primary mirror of the Keck telescope.



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Keck Primary Tesselation

Primary mirror specifications

- Concave hyperboloid
- k = -1.003683
- R = 34.974 m
- F 1.75
- 10 m aperture
- 359 mm sag
- 36, 1.8 m segments
- 75 mm thick, 400 kg ea

< 204 µm FTS excursion

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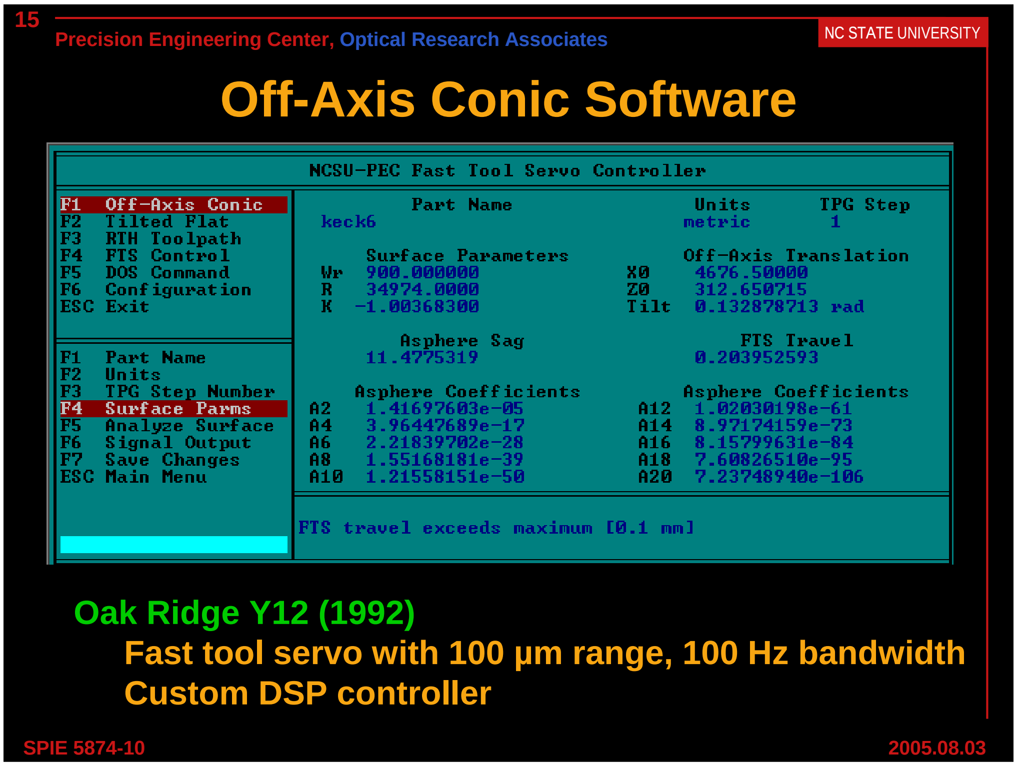
- Example parameters shown are for the segment with the largest sag for the Keck hyperbolic primary
- Segments numbered 6 (in red) have the largest NRS sag

- Primary segments could be machined on a DTM with 1.8 m capacity and a Variform fast tool servo (400 µm range)



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Off-Axis Conic Software

```
                    NCSU-PEC Fast Tool Servo Controller

F1  Off-Axis Conic          Part Name                       Units      TPG Step
F2  Tilted Flat        keck6                             metric        1
F3  RTH Toolpath
F4  FTS Control           Surface Parameters             Off-Axis Translation
F5  DOS Command        Wr   900.000000              X0     4676.50000
F6  Configuration      R    34974.0000              Z0     312.650715
ESC Exit               K  -1.00368300               Tilt   0.132878713 rad

                              Asphere Sag                    FTS Travel
F1  Part Name               11.4775319                   0.203952593
F2  Units
F3  TPG Step Number       Asphere Coefficients           Asphere Coefficients
F4  Surface Parms      A2   1.41697603e-05           A12   1.02030198e-61
F5  Analyze Surface    A4   3.96447689e-17           A14   8.97174159e-73
F6  Signal Output      A6   2.21839702e-28           A16   8.15799631e-84
F7  Save Changes       A8   1.55168181e-39           A18   7.60826510e-95
ESC Main Menu          A10  1.21558151e-50           A20   7.23748940e-106

                     FTS travel exceeds maximum [0.1 mm]
```

Oak Ridge Y12 (1992)

Fast tool servo with 100 µm range, 100 Hz bandwidth

Custom DSP controller

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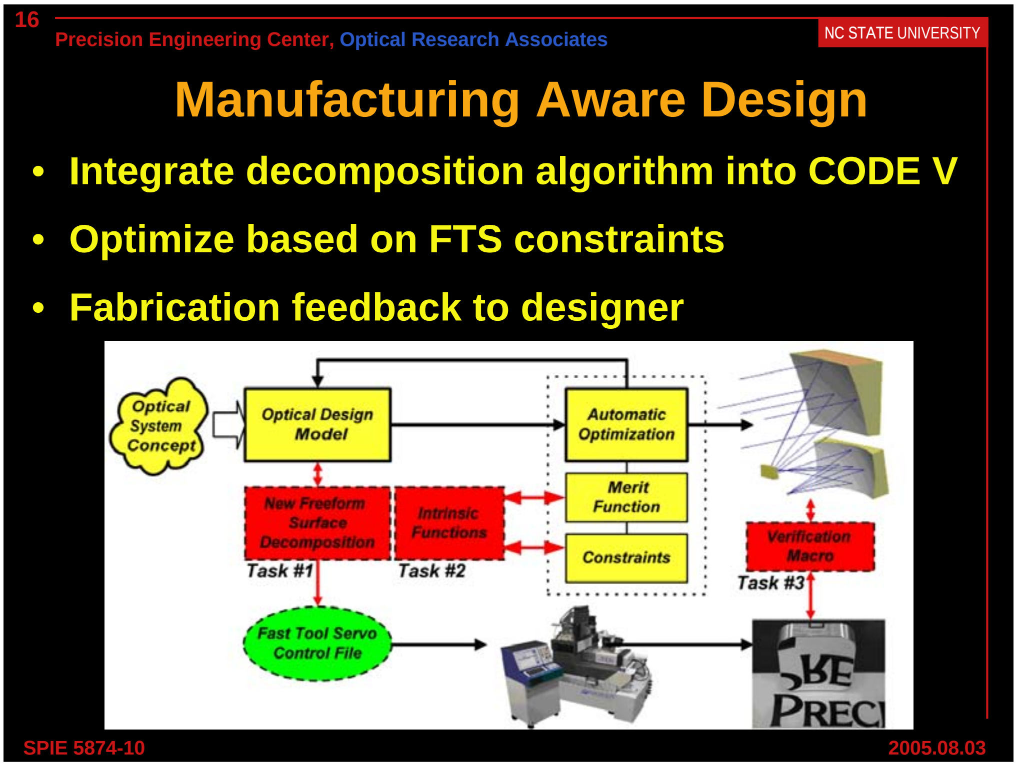
- Main screen of custom controller software developed for Oak Ridge Y12 is shown
- Automatically generates part programs for both the base DTM asphere and the FTS coefficients (auto downloads to both controllers)
- Input parameters: Wr (workpiece radius), X_0 (decenter), K (conic constant), R (conic radius)
- Best-fit asphere sag, coeffieients, FTS excursion and tilt angle (normal at center of aperture with respect to back surface) are displayed on the screen
- Patented in 1995, US 5,467,675
- Optimized C code for use in a real-time controller for the FTS running at a 30 kHz servo update rate
- Code was re-written as a DLL for use by Code V



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Manufacturing Aware Design

- **Integrate decomposition algorithm into CODE V**
- **Optimize based on FTS constraints**
- **Fabrication feedback to designer**

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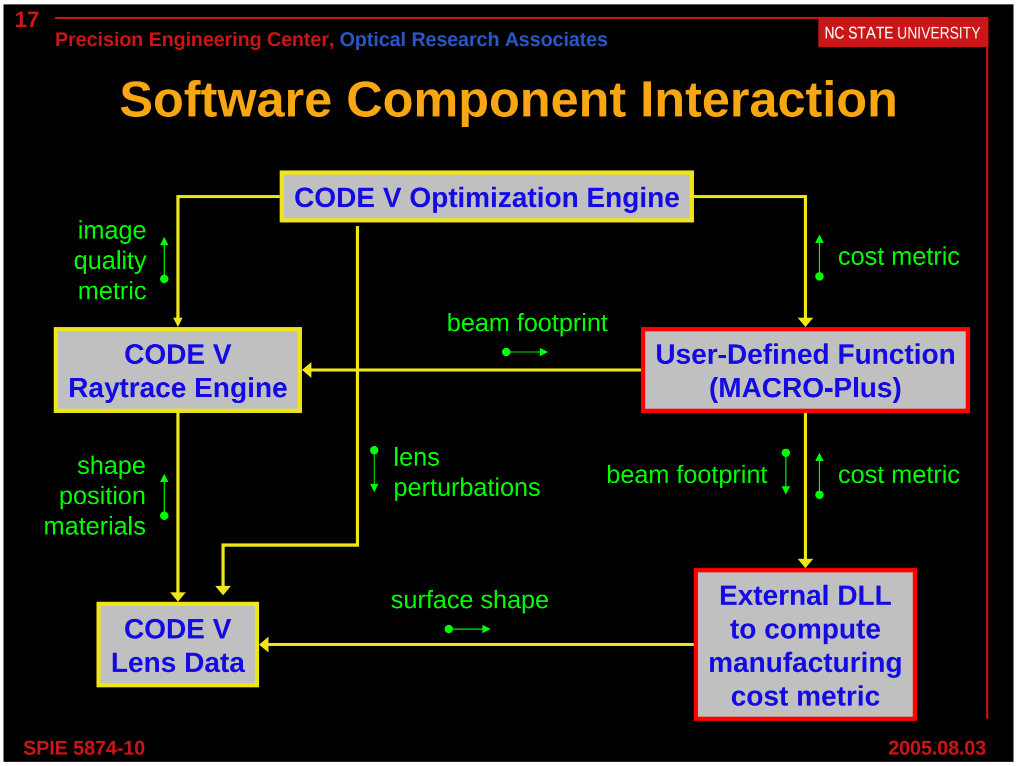
- Project tasks are shown in red boxes

- Available in future release of CODE V (soon), contact ORA for details



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Software Component Interaction

CODE V Optimization Engine

image quality metric

cost metric

beam footprint

CODE V Raytrace Engine

User-Defined Function (MACRO-Plus)

shape position materials

lens perturbations

beam footprint

cost metric

surface shape

CODE V Lens Data

External DLL to compute manufacturing cost metric

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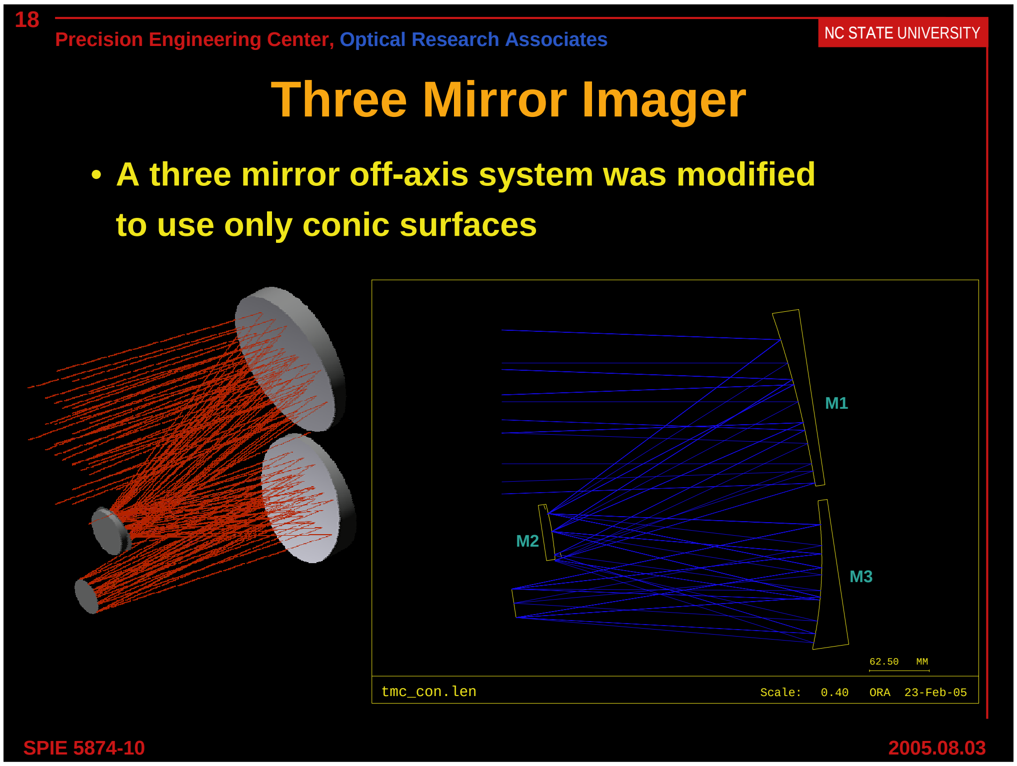
- ORA modified MACRO-Plus to call external DLLs
- External DLL code is optimized C for efficiency
- Access to lens database from DLL
- Optimizer can change conic parameters, decenter, beam footprint

- Extensible to other surface types



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Three Mirror Imager

- A three mirror off-axis system was modified to use only conic surfaces

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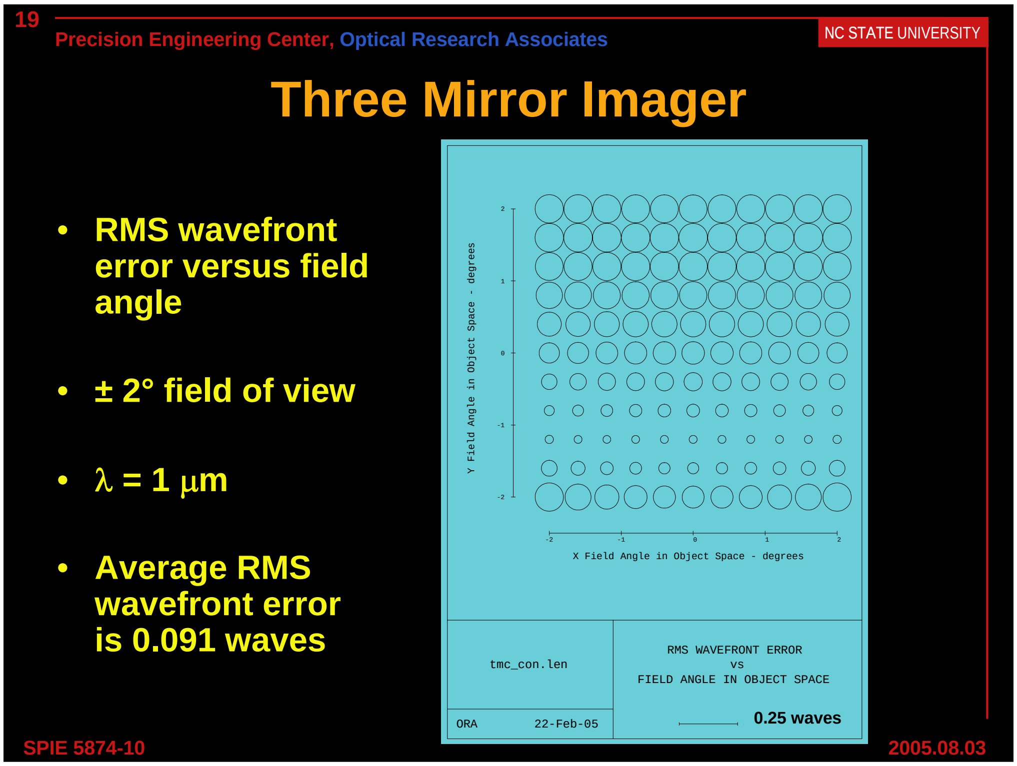
- Two systems were optimized using the new merit function for freeform surfaces

- A three mirror imager is shown
- A four mirror afocal system was also optimized with similar results, see Appendix
- Both are described in the proceedings paper



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Three Mirror Imager

- RMS wavefront error versus field angle
- ± 2° field of view
- λ = 1 μm
- Average RMS wavefront error is 0.091 waves

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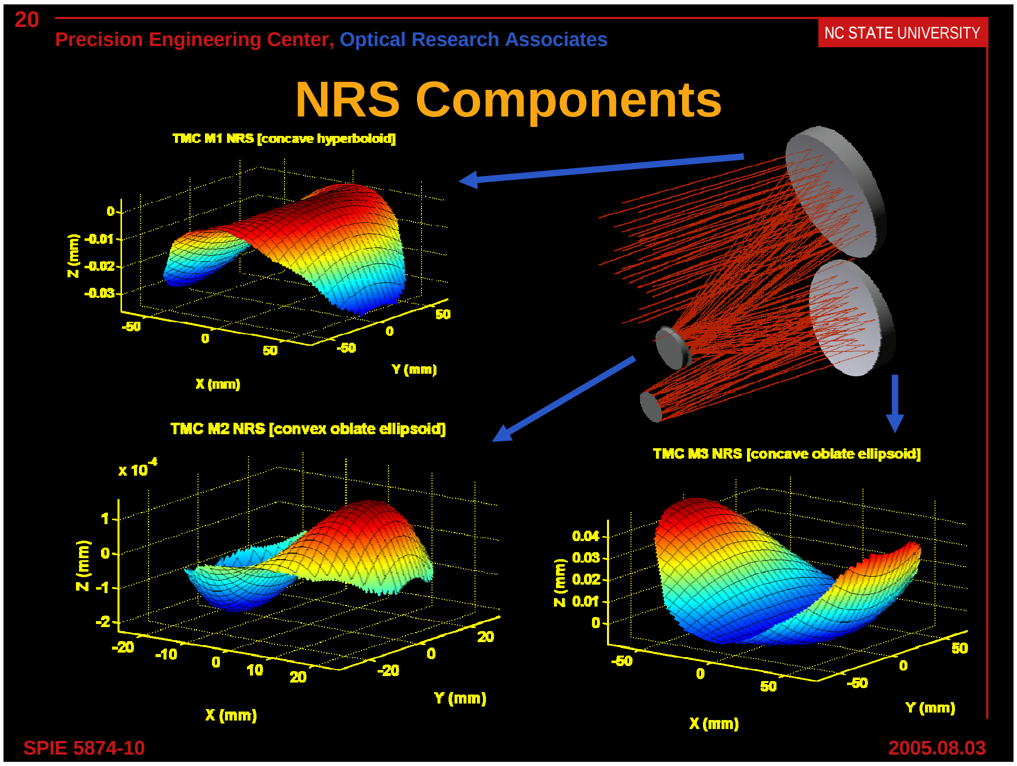

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NRS Components

TMC M1 NRS [concave hyperboloid]

TMC M2 NRS [convex oblate ellipsoid]

TMC M3 NRS [concave oblate ellipsoid]

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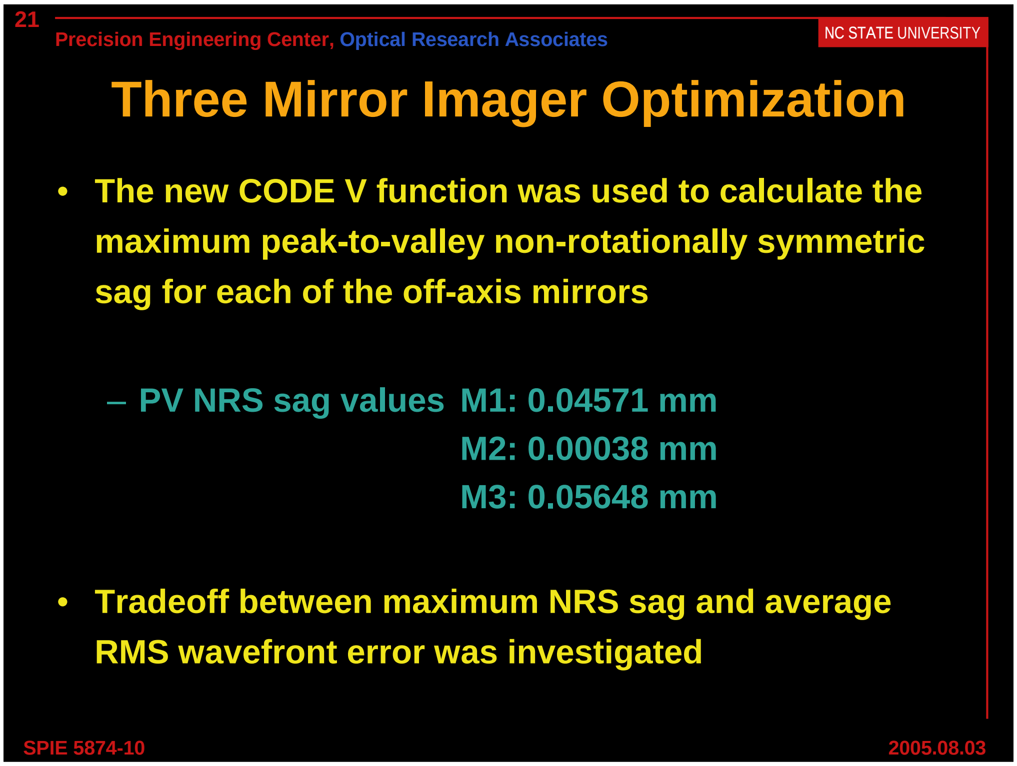
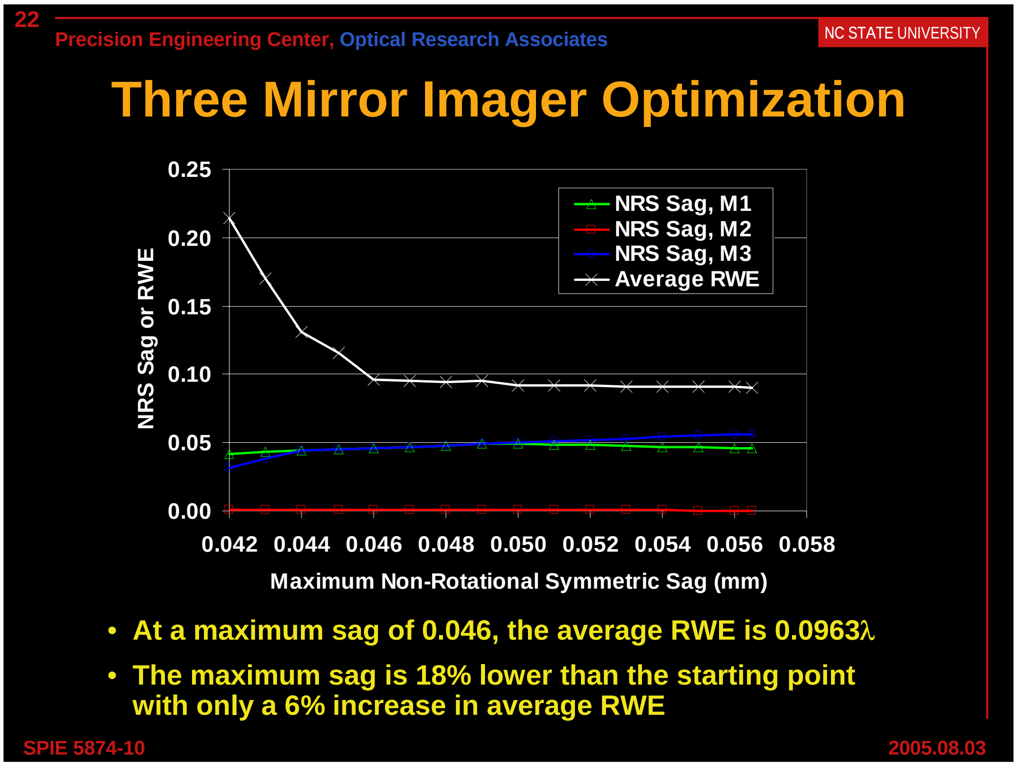
- The plots show the decomposed NRS component of each mirror surface



Three Mirror Imager Optimization

- **The new CODE V function was used to calculate the maximum peak-to-valley non-rotationally symmetric sag for each of the off-axis mirrors**
  - **PV NRS sag values M1: 0.04571 mm**
    M2: 0.00038 mm
    M3: 0.05648 mm
- **Tradeoff between maximum NRS sag and average RMS wavefront error was investigated**

- The optimizer minimizes NRS sag (ie, cost) without introducing excessive wavefront error



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Three Mirror Imager Optimization

- At a maximum sag of 0.046, the average RWE is 0.0963λ
- The maximum sag is 18% lower than the starting point with only a 6% increase in average RWE

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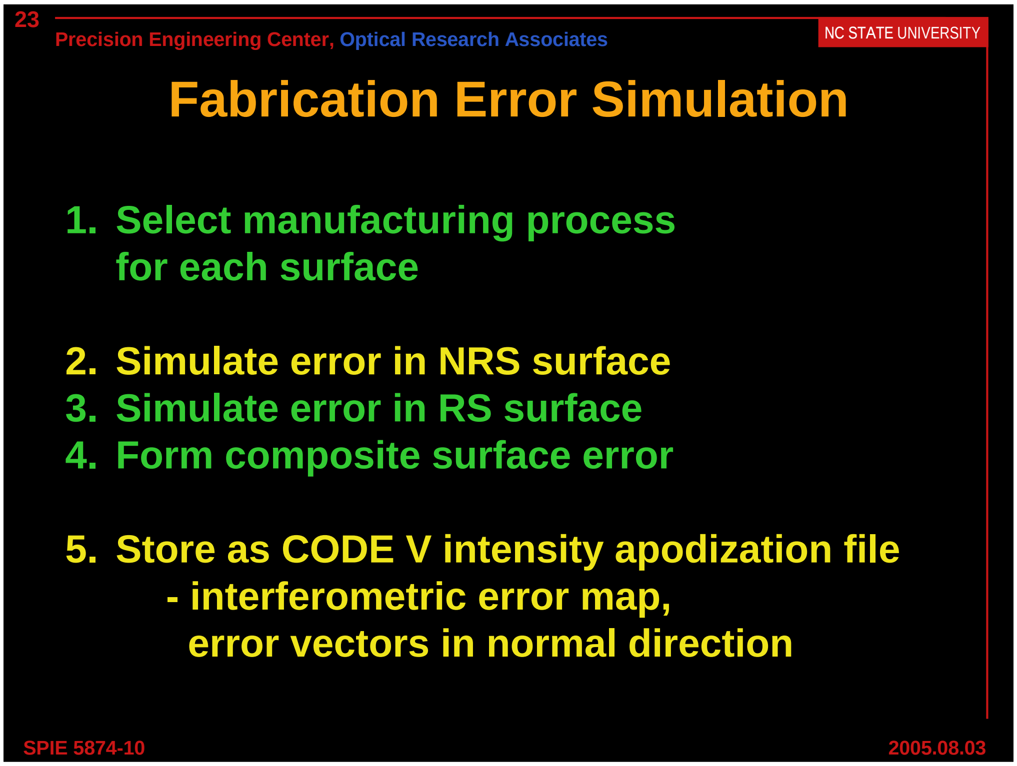
- Plot shows maximum NRS sag of all mirrors over beam footprint (horizontal axis) vs NRS sag of individual mirrors and RWE of entire system (vertical axis)
- Process starts at the far right in the graph
- RWE begins to increase rapidly at 0.046 mm maximum NRS sag



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Fabrication Error Simulation

1. Select manufacturing process for each surface

2. Simulate error in NRS surface
3. Simulate error in RS surface
4. Form composite surface error

5. Store as CODE V intensity apodization file
   - interferometric error map, error vectors in normal direction

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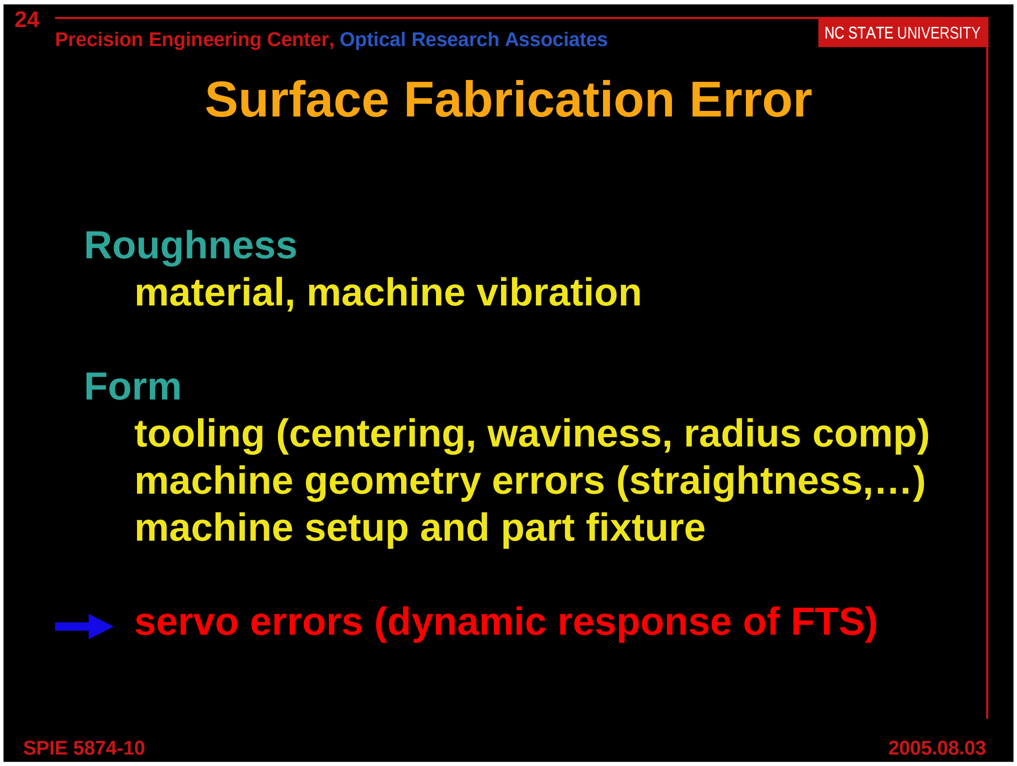


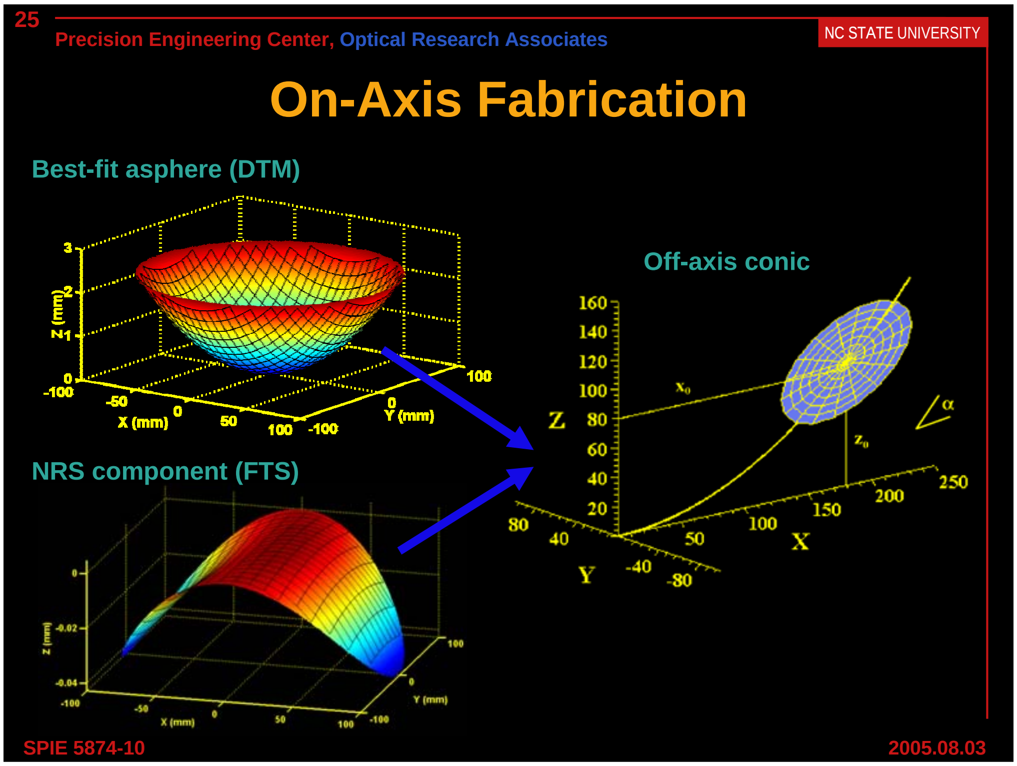
Surface Fabrication Error

Roughness
material, machine vibration

Form
tooling (centering, waviness, radius comp)
machine geometry errors (straightness,…)
machine setup and part fixture

→ servo errors (dynamic response of FTS)

- Only errors due to FTS dynamics were simulated



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On-Axis Fabrication

Best-fit asphere (DTM)

Off-axis conic

NRS component (FTS)

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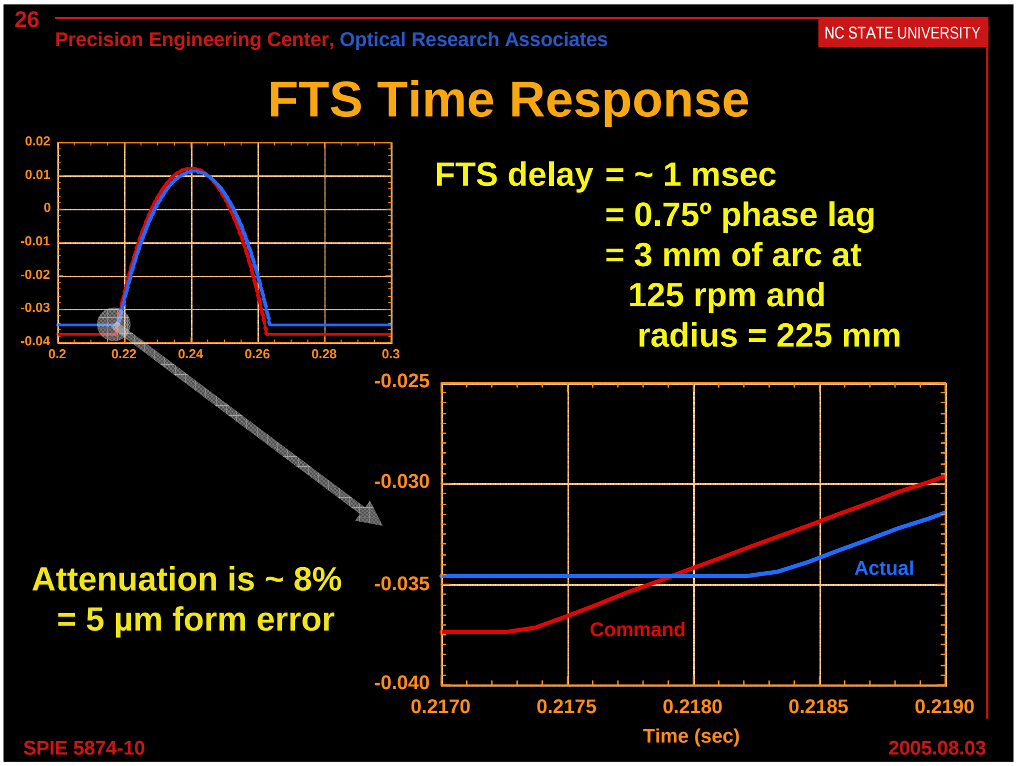
- Asphere and NRS surface must be machined simultaneously with perfect synchronization to “add-up” to the desired off-axis conic



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FTS Time Response

FTS delay = ~ 1 msec
= 0.75º phase lag
= 3 mm of arc at
125 rpm and
radius = 225 mm

Attenuation is ~ 8%
= 5 µm form error

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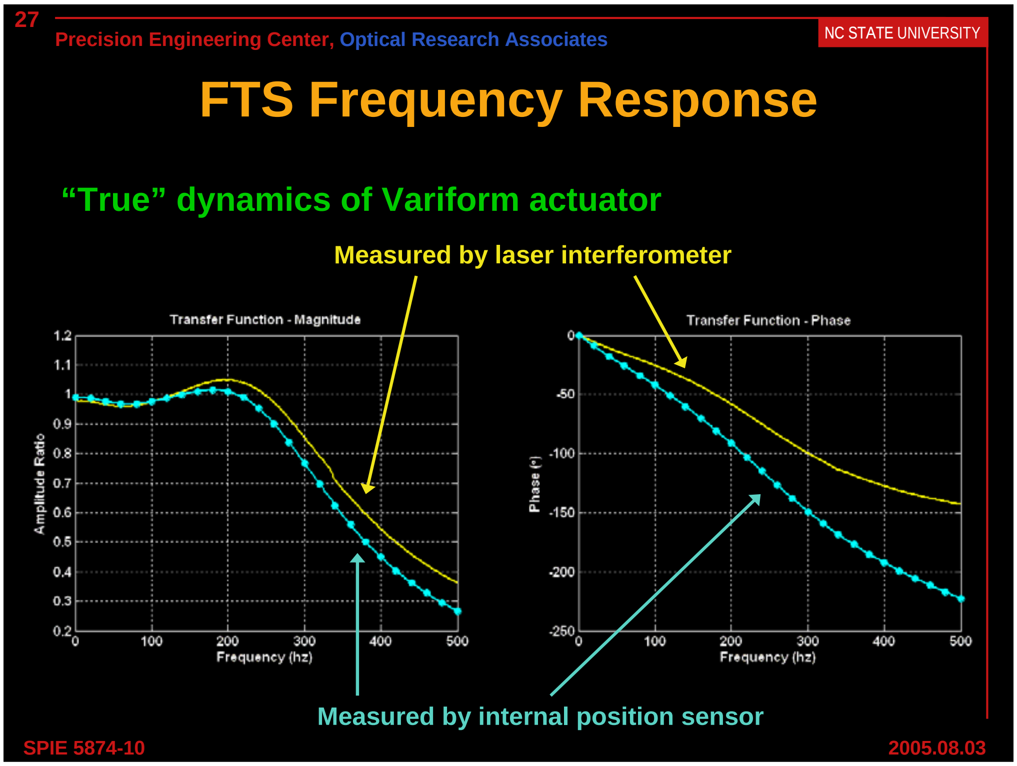
- Plots show measurement of FTS command signal (in red) and FTS motion (via LVDT feedback, in blue)
- Note the shift in time and the attenuated amplitude
- Vertical offset in plots is artificial
- Explanation - the FTS has both phase lag and signal attenuation
- Phase error scales with radius

- Example shows data for IRMOS M4 off-axis machining with a Variform FTS



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FTS Frequency Response

“True” dynamics of Variform actuator

Measured by laser interferometer

Measured by internal position sensor

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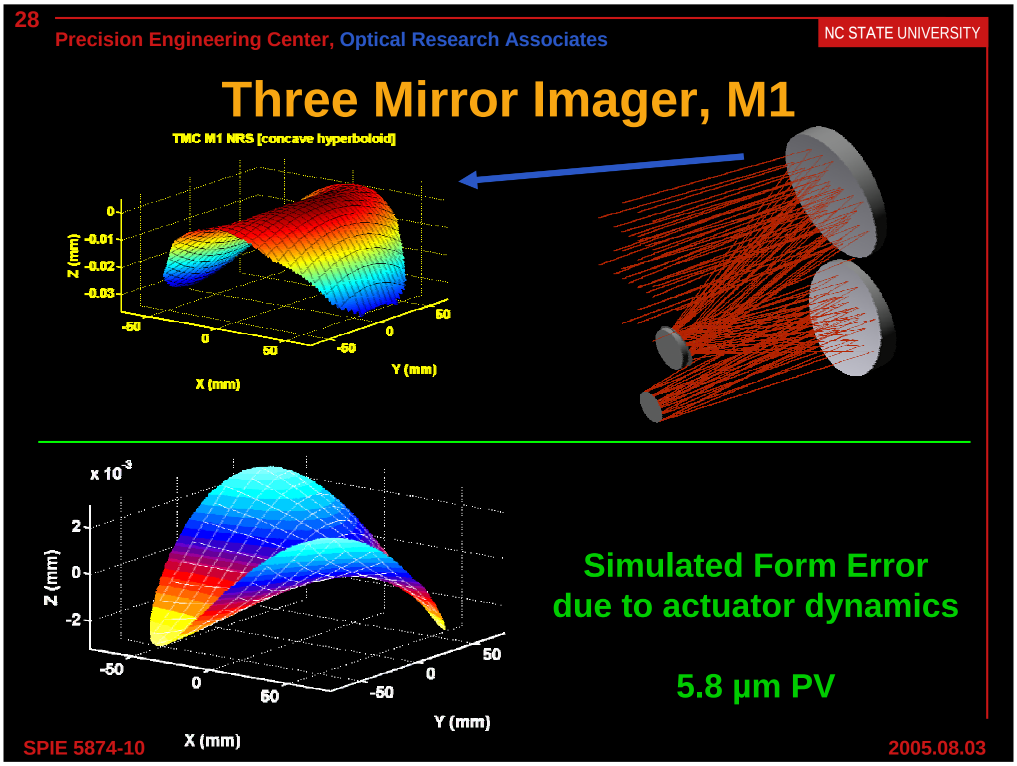
- Dominate phase error is at integer multiple of spindle rotation frequency
- For example, a toric would have form phase error from 2x spindle frequency



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Three Mirror Imager, M1

Simulated Form Error
due to actuator dynamics

5.8 µm PV

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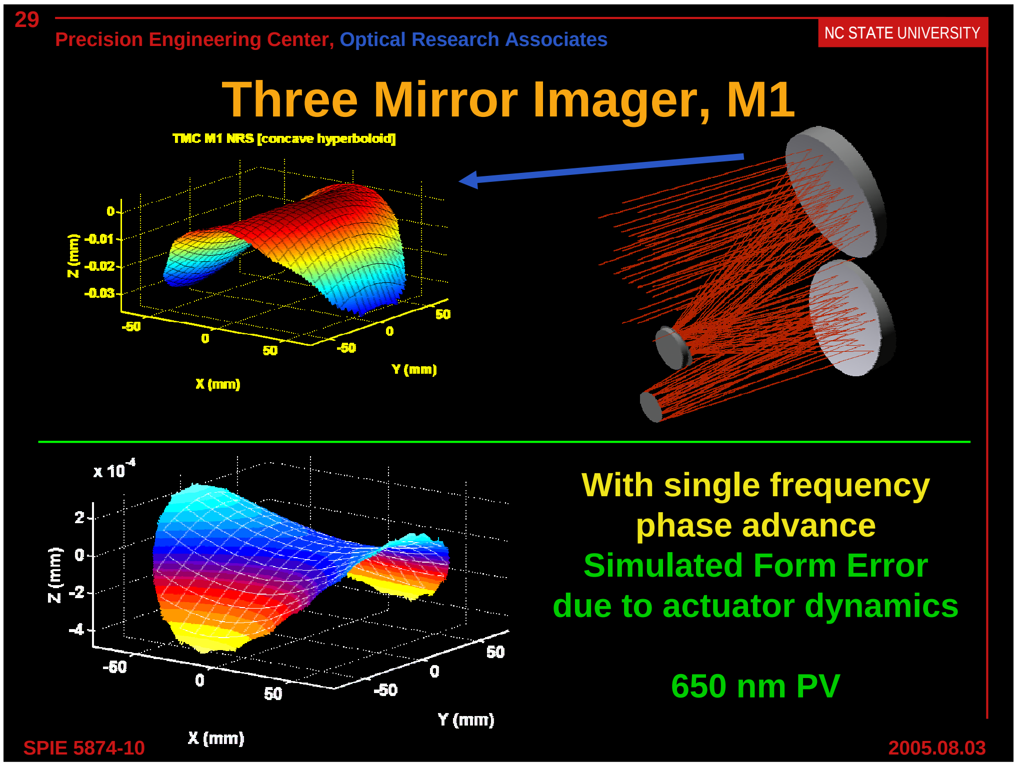
- Errors due to dynamics for all mirrors in both systems were simulated by convolution of actuator impulse response with time domain NRS shape
- Lower plot show form error for M1 if actuator dynamics are uncorrected



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Three Mirror Imager, M1

With single frequency phase advance

Simulated Form Error due to actuator dynamics

650 nm PV

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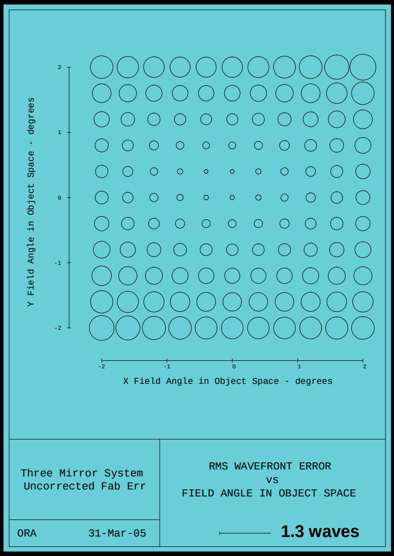
- Clocking error correction has been applied to correct phase error at spindle frequency
- The trajectory signal for the FTS has been time advanced by the amount indicated
  on the phase response plot at the frequency of spindle rotation (1200 rpm = 20 Hz)

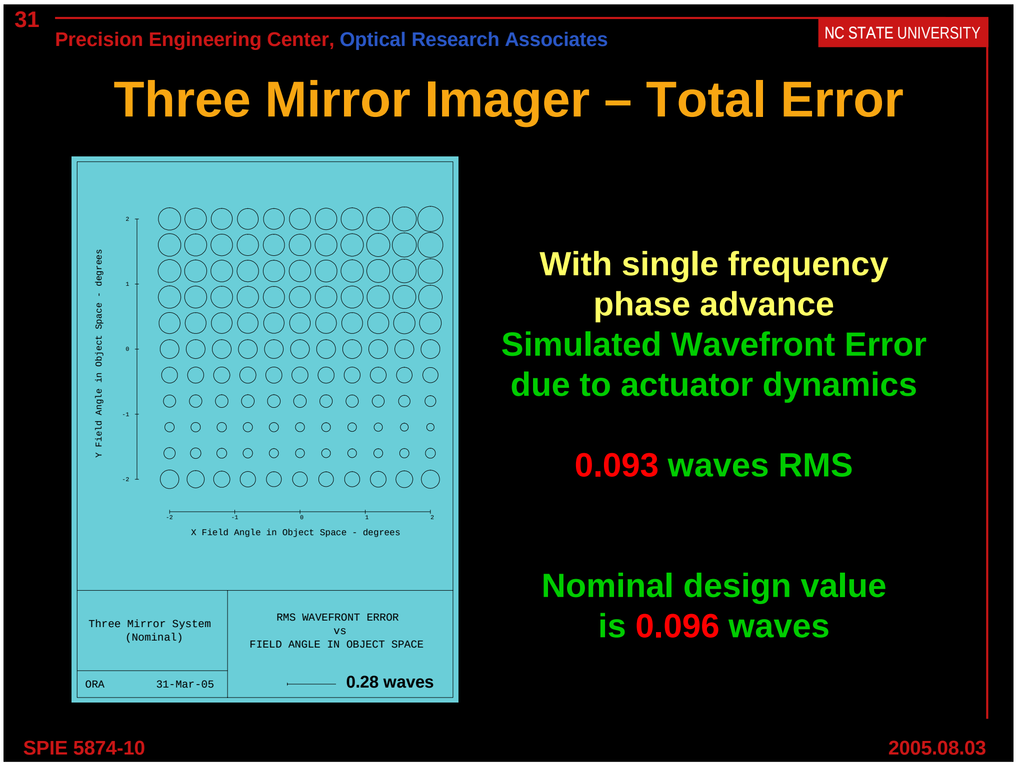
Three Mirror Imager – Total Error



Simulated Wavefront Error due to actuator dynamics

0.367 waves RMS

Nominal design value is 0.096 waves



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Three Mirror Imager – Total Error

With single frequency phase advance
Simulated Wavefront Error due to actuator dynamics

0.093 waves RMS

Nominal design value is 0.096 waves

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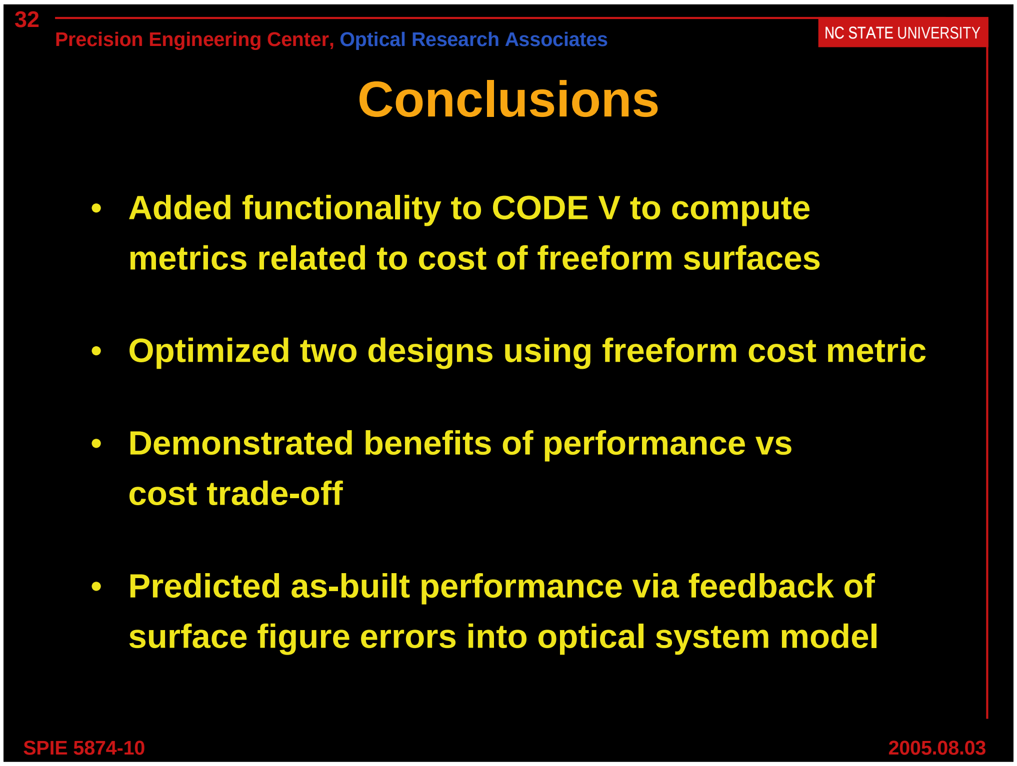
- By serendipity the non-conic shape of the as-built mirrors gives a lower wavefront error; perhaps anamorphic surfaces would be better

- Note the scale change and the location of the minimum error



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Conclusions

- Added functionality to CODE V to compute metrics related to cost of freeform surfaces
- Optimized two designs using freeform cost metric
- Demonstrated benefits of performance vs cost trade-off
- Predicted as-built performance via feedback of surface figure errors into optical system model

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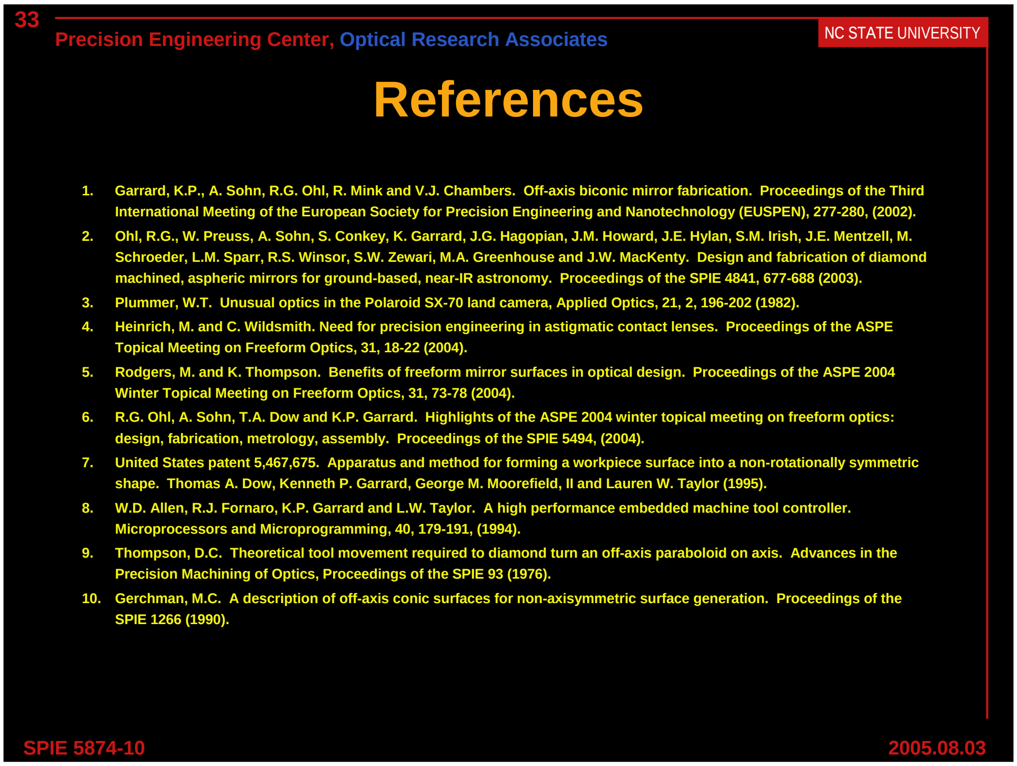
The ability of an optical designer to obtain early feedback about the manufacturability and cost of a freeform surface will ultimately lead designers to employ these surfaces in those designs where the benefits are worth the added cost. In the past, it has been the case that a designer is completely unsure of what that added cost is, and thus there is no easy way for a compromise between cost and performance to be made for systems utilizing freeform shapes.



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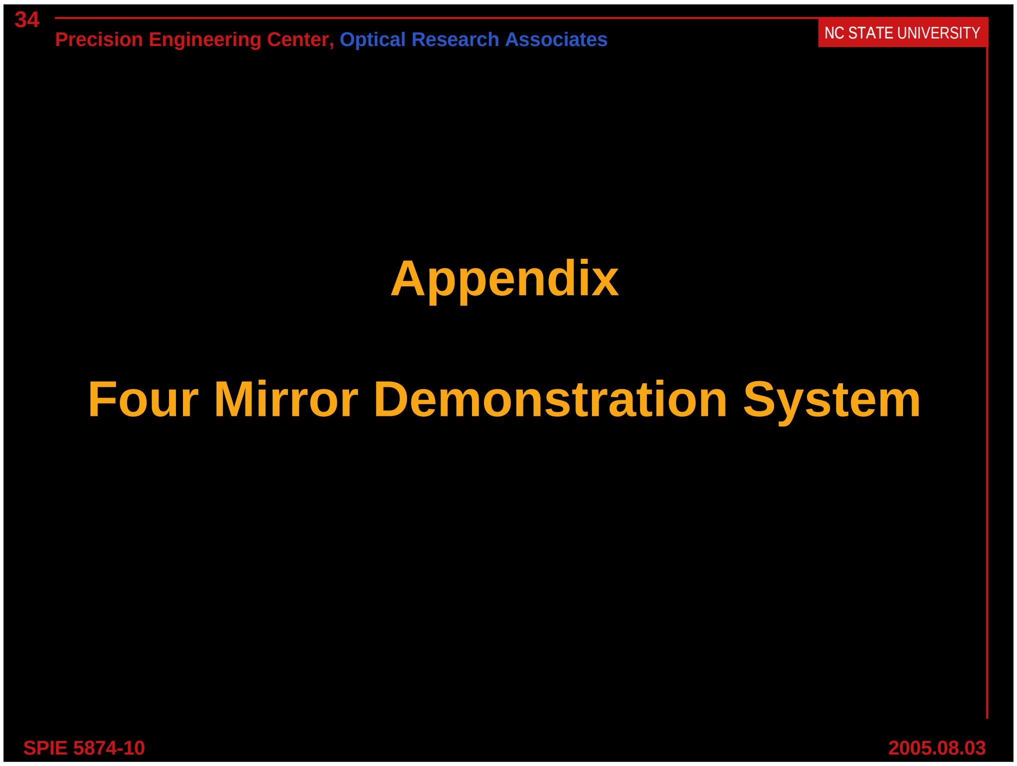
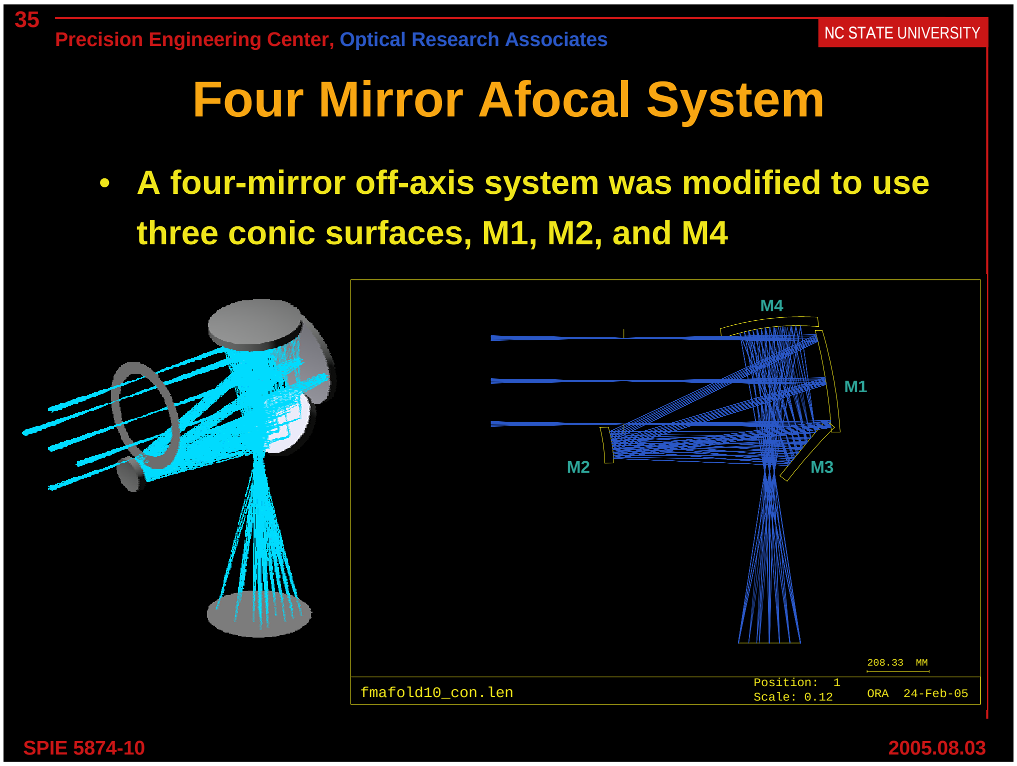


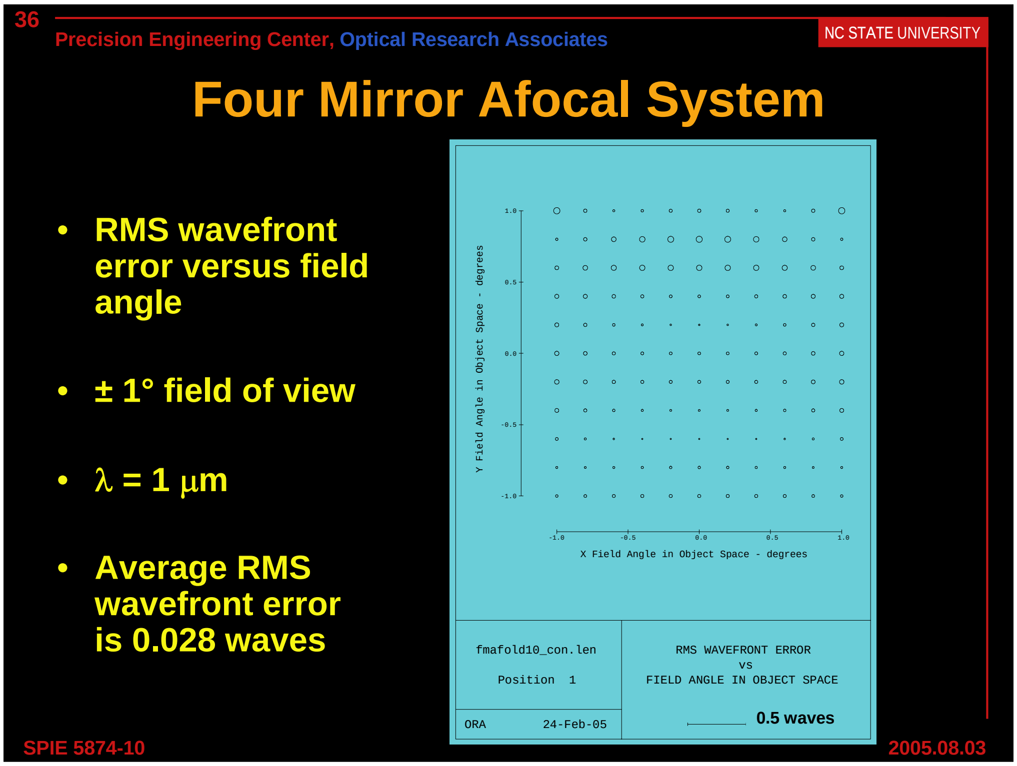
Appendix

Four Mirror Demonstration System



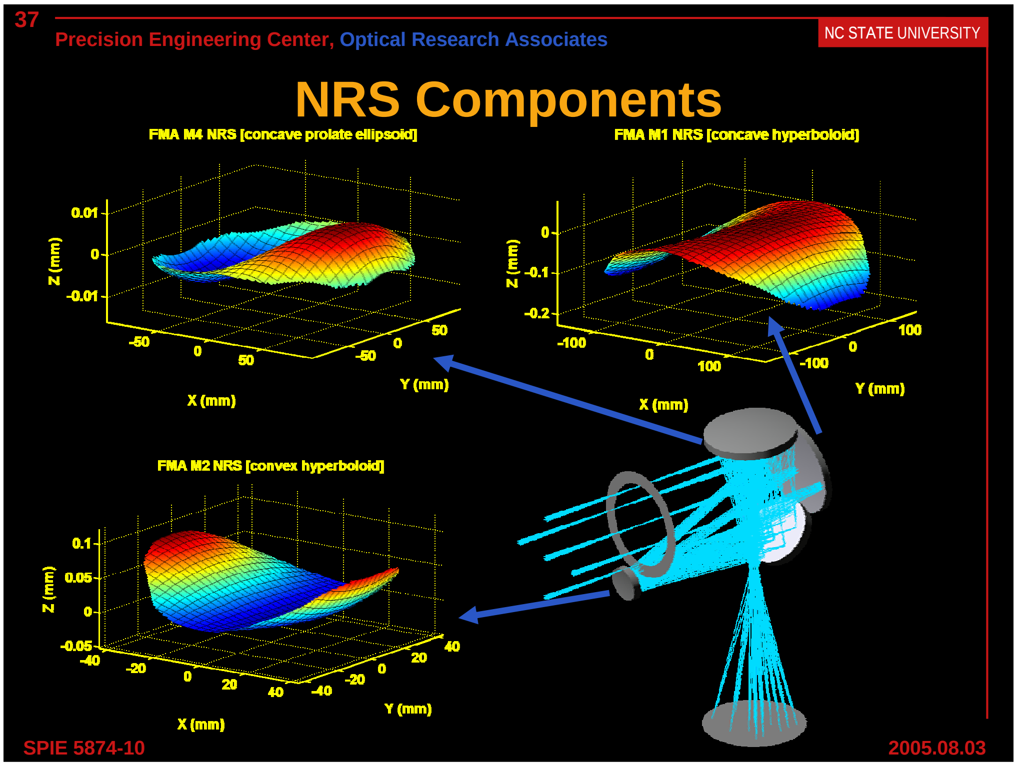
Four Mirror Afocal System

- A four-mirror off-axis system was modified to use three conic surfaces, M1, M2, and M4



Four Mirror Afocal System

- RMS wavefront error versus field angle
- ± 1° field of view
- $\lambda = 1\ \mu m$
- Average RMS wavefront error is 0.028 waves



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NRS Components

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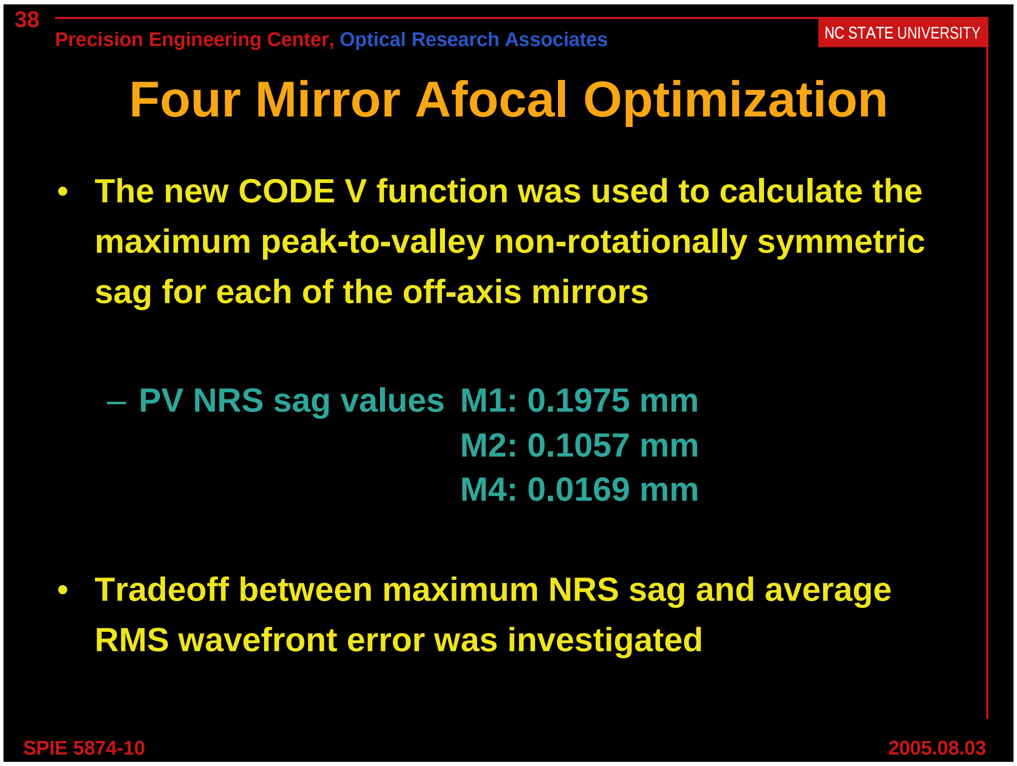
- The plots show the decomposed NRS component of each mirror surface



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Four Mirror Afocal Optimization

- The new CODE V function was used to calculate the maximum peak-to-valley non-rotationally symmetric sag for each of the off-axis mirrors
  - PV NRS sag values M1: 0.1975 mm
    M2: 0.1057 mm
    M4: 0.0169 mm
- Tradeoff between maximum NRS sag and average RMS wavefront error was investigated

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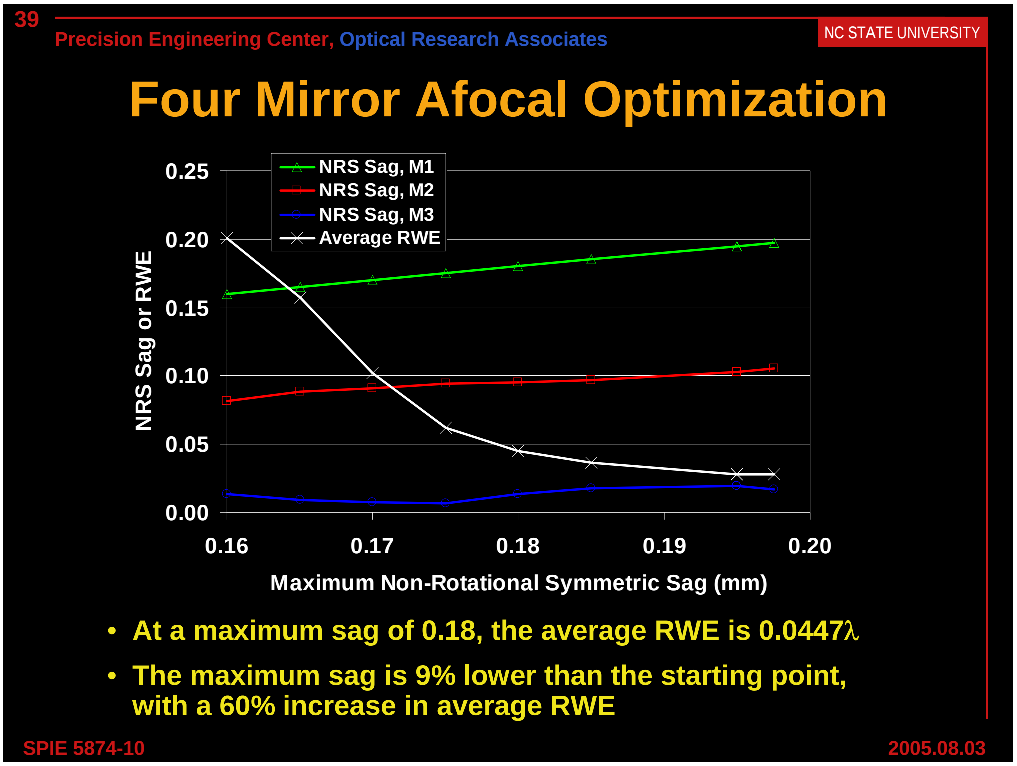
- The optimizer minimizes NRS sag (ie, cost) without introducing excessive wavefront error



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Four Mirror Afocal Optimization

- At a maximum sag of 0.18, the average RWE is 0.0447λ
- The maximum sag is 9% lower than the starting point, with a 60% increase in average RWE

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- Plot shows maximum NRS sag of all mirrors over beam footprint (horizontal axis) vs NRS sag of individual mirrors and RWE of entire system (vertical axis)
- Process starts at the far right in the graph
- RWE begins to increase rapidly at 0.18 mm maximum NRS sag

- Percent change is lower, but NRS sags are much higher than in the three mirror system