K. Lyon Folder 13 Structural ppt
120.11 + 7 Videos

Terrestrial Planet Finder Mission

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Structural Modeling and Analysis

Andy Kissil

(with inputs from Eug Kwack & Tim Ho)

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Presentation Overview

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- Model Description
  - Primary Mirror
  - Observatory (Science Payload + Support Module)
  - Sun-shield & Solar-Sail
- System Normal Modes Analysis
- Thermal Distortion Analysis
  - 20 deg Dither from 80 to 100 deg & 170 to 190 deg
    - Primary Mirror
      - Uniform Primary Mirror CTE
      - Variable Primary Mirror CTE
    - Telescope

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Model Description

Modeling Assumptions

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Major Assumptions & Approach:

- Baseline point-design: not optimal or final design
- 10 m Long Cassegrain Telescope
- Light-weighted ULE primary mirror (discussed later)
  - mirror mounts not modeled in detail
- Structural material properties are constant (not time dependent)
- Passive ~1 Hz Spacecraft/AMS mount interface (for isolation)
  - Investigating industry-produced active isolation systems that may perform two to three orders of magnitude better than passive
- Joints not modeled in detail: i.e. perfect flexures, no fitting details
- Sun-shield and solar sail
  - No tensioning cable vibration effects modeled (can be added)
  - No membrane wrinkling effects accounted for
  - 2.54e-5 m thick (.001") Kapton, with non-struc mass of 0.0085kg/m^2
  - pre-tensioned membranes modeled using equivalent geometric stiffness
    - uniform membrane pre-stress assumed: no in-plane variation
    - 3 psi pre-tension for sun-shield
    - 6 psi pre-tension in solar-sail
- One to one node correspondence between structural & thermal models except for processing high-fidelity primary mirror temperatures

Normal Vibration Modes & Thermal Distortion

Analysis codes used: NASTRAN & IMOS

Primary Mirror Models

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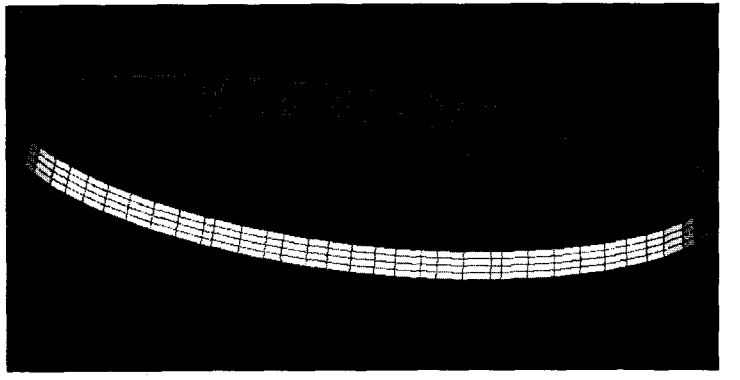
Low Fidelity: [423 Nodes (2,538 dofs), 770 Elements]

- Single layer of 2D plate elements with effective bending & shear
- Matches overall mirror mass properties & vib modes well
- Neglects through thickness compliance at mounts
- Cannot model print-through
- Used for most dynamic response analyses

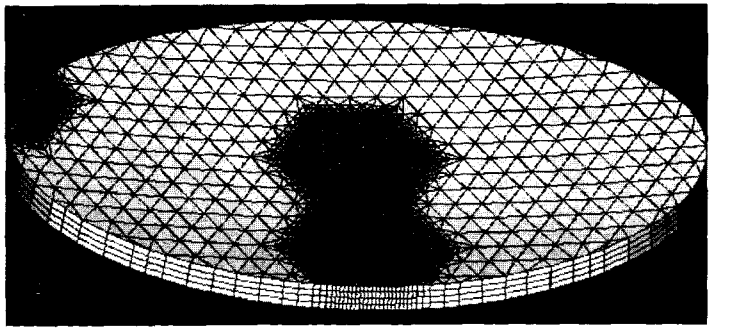
Mid Fidelity: [2115 Nodes (12,690 dofs), 4620 Elements]

- 2 Layers of 2d plate elements (front and back face-sheets)
- 4 Layers of solid elements with effective core properties
- Matches overall mirror mass properties & vib modes well
- Captures through-thickness compliance, but not at cell resolution
- Cannot model print-through
- No core segmentation modeled
- Used for most thermal distortion analyses



High Fidelity: [15,953 Nodes (95,718 dofs); 30,816 Elements]

- Hybrid Model (to minimize computation time/size)
  - Core and face-sheets modeled with plate elements
  - 18 segments have core modeled with equivalent solid elements
  - 3 segments have core modeled with plate elements
- Captures thru-thickness compliance (at cell resolution for local areas)
- Captures print-through for localized areas
- Captures spacing effects between core segments
- Used to spot-check Mid-Fidelity model results



System Model

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Configuration: **Mv3b-D**

System model with **Low Fidelity** primary mirror:

Number of nodes = 2813 (~17,000 dofs)
Number of elements = 3620

Sci Payload model with Low Fidelity primary mirror:

Number of nodes = 1969 (~12,000 dofs)
Number of elements = 2647

System model with **High Fidelity** primary mirror:

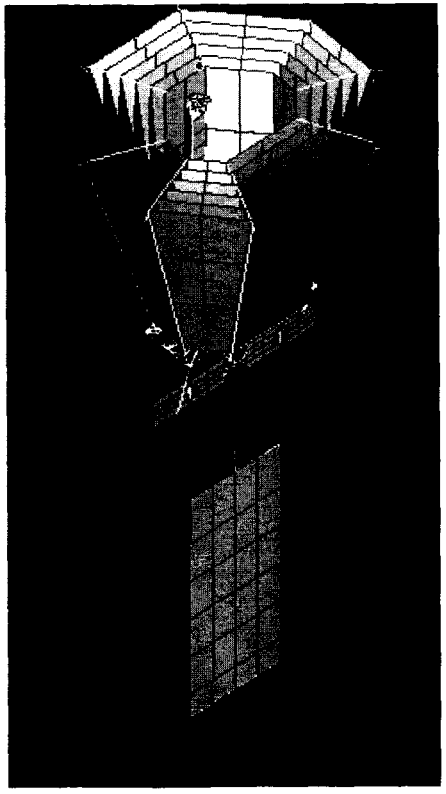
Number of nodes = 18,334 (~110,000 dofs)
Number of elements = 33,659

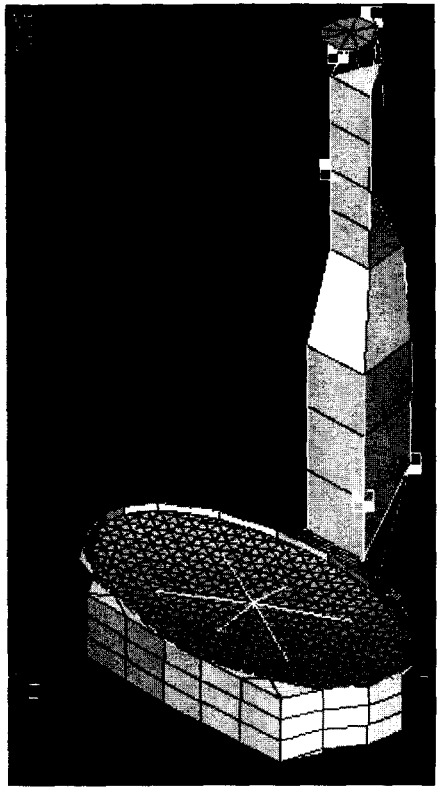
Sci Payload model with High Fidelity primary mirror:

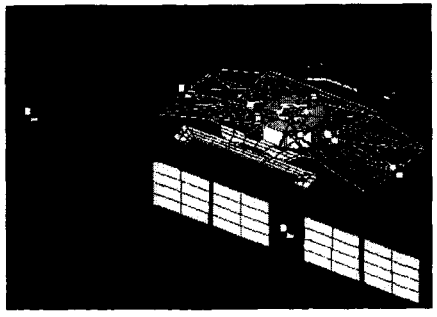
Number of nodes = 17,490 (~105,000 dofs)
Number of elements = 32,686

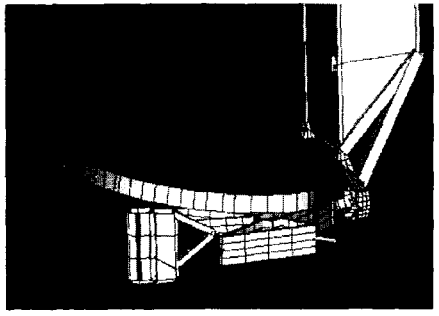
Support Module model with High Fidelity primary mirror:

Number of nodes = 844 (~5,000 dofs)
Number of elements = 967









System Model Mass Properties

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The 6x6 rigid **System** (TPFC_Mv3b_D_LF) mass (kg, kg-m^2) about cg:

5.3551e+003	4.7004e-014	3.4440e-014	-3.9029e-014	6.8785e-011	-2.9148e-011
4.8061e-014	**5.3551e+003**	2.4895e-014	-6.9031e-011	5.7123e-015	1.0170e-013
3.8097e-014	2.1431e-014	**5.3551e+003**	2.9479e-011	-4.4409e-014	1.2832e-014
-2.9047e-014	-6.9031e-011	2.9500e-011	**5.0131e+004**	4.7616e+002	2.8143e+000
6.9012e-011	2.7357e-014	-8.7041e-014	4.7616e+002	**5.5411e+004**	-2.4392e+003
-2.9207e-011	1.1591e-013	2.2174e-014	2.8143e+000	-2.4392e+003	**2.5855e+004**

Total observatory mass (kg) = **5355 kg**
System c.g.(m) = [-0.007183 1.833057 12.933685]

distance from RW cg is **0.807**m
[.0072 0.1830 0.7856]

Total science payload mass (kg) = 3600 kg
Payload c.g.(m) = [-0.008384 1.750663 12.679328]

Total Support Module mass (kg) = 1755 kg
Support Module c.g.(m) = [-0.004720 2.002051 13.455382]

Item Description	Mass (kg)
Bus:	215
Truss (thermal shade & S/C equip)	632 (*)
Reaction Wheel Support Structure	27
Thermal shade support panels	80
Solar array booms	12
Solar sail booms	52
Antenna booms	10
Thermal shade canisters & booms	82
Thermal shade spreader bars	85
V-groove layers including baffle	83
Solar array panels	40
Thruster clusters	5
M1	754
M1 metering structure	1340 (*)
M1 support bipods	30
M1 thermal cavity housing	235
Optical bench and housing	400
Optical bench bipods	30
M2	10
M2 support bracket	10
M2 hexapod	5
M2 tower support bracket	470 (*)
M2 tower	370
Prop tanks & prop mass	500

(*) The design for these items have not been optimized, hand have significant room for mass reduction

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Sun-shield & Solar-Sail Models

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Pre-tensioned Membrane Modeling:

Use standard plate element effective shear stiffness to represent geometric stiffness (differential stiffness)

- Better than using bending stiffness: frequencies increase with i (mode no.), rather than with i^2 as with bending
- Similar method can be used for load-stiffened cables and softened beams
- No artificial grounding of stiffness matrix (bad for free-free structures)
- In-plane membrane properties are maintained as usual
- Process:

  Set **shear factor = preload stress/G,** where G= shear modulus

  (can assume uniform preload stress, or compute per element)

  Set bending factor very high (bending mode freqs> freq interest range)

  Sun-shield example:

  Preload stress = 20703 N/m^2 (3psi)

  G = 1.312e+9 N/m^2 (190 ksi, for the Kapton)

  Shear factor (TS/T in NASTRAN) = 1.578E-5= 20703/1.312E+9
  Bending factor (12I/T^3 in NASTRAN) = 1e+9

Sun-shield Normal Modes

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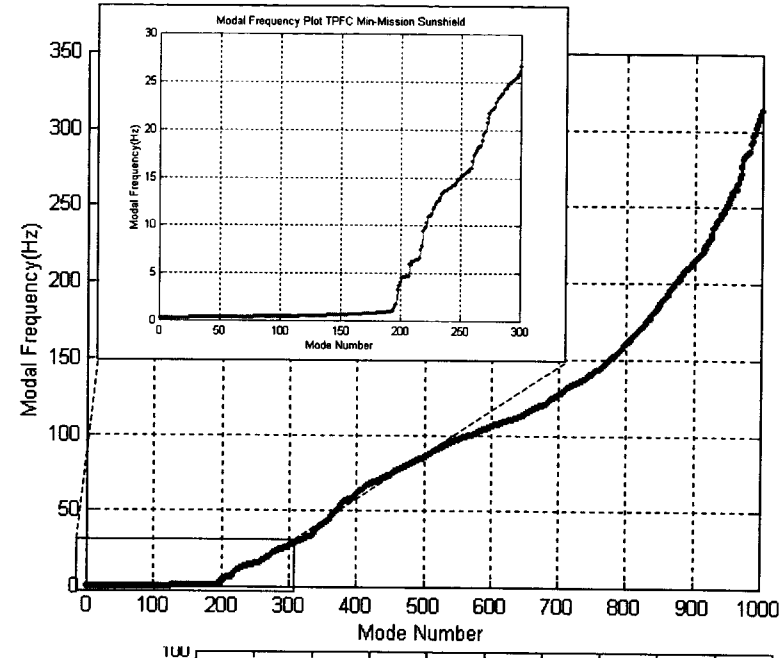
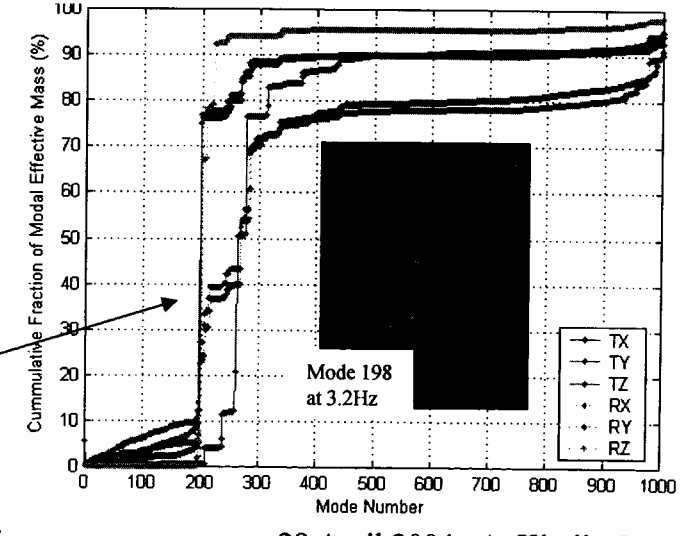
Cantilevered Sun-shield Normal Modes:

- 0.23 Hz lowest mode
- ~200 modes below 1 Hz
- 1st 300 modes (~25 Hz) capture ~70% of effective mass





Cumulative Fraction of Modal Effective Mass (%)

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System Normal Modes Analysis

Dynamic Vibration: System Normal Modes Analysis

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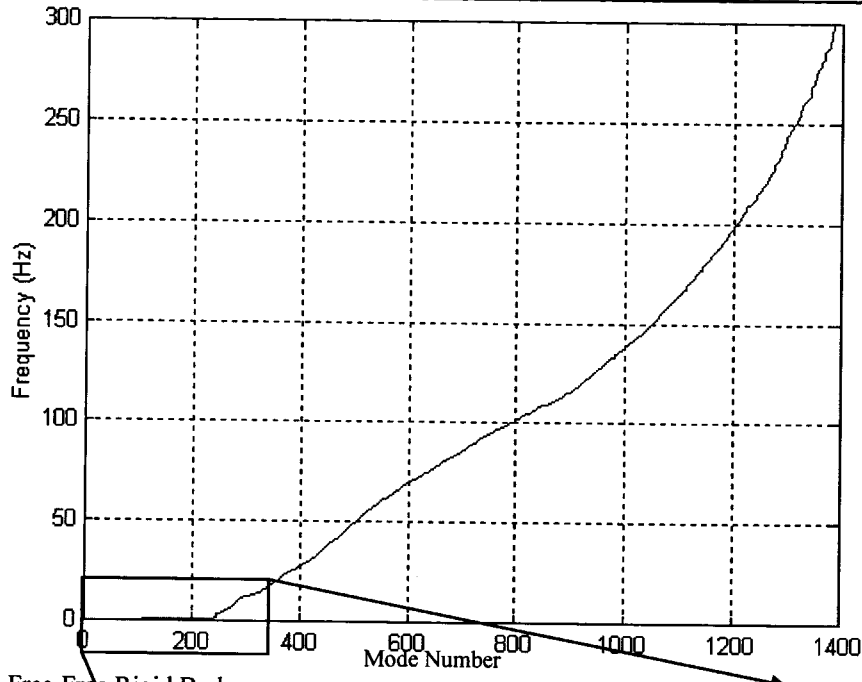
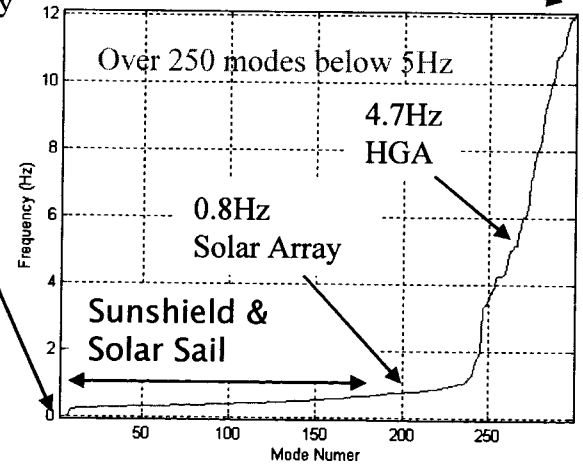
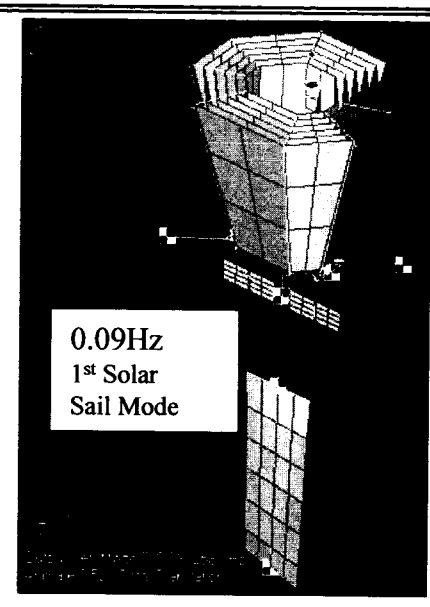
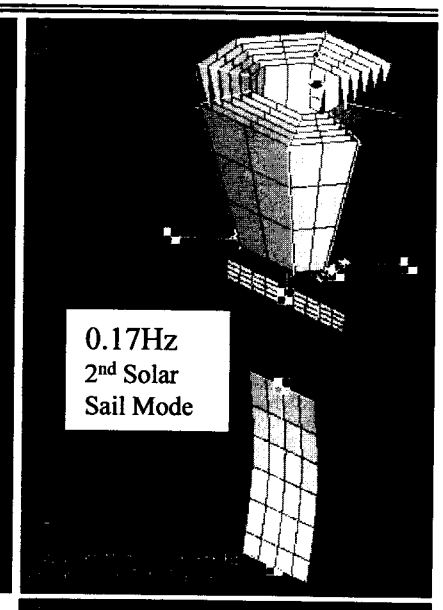
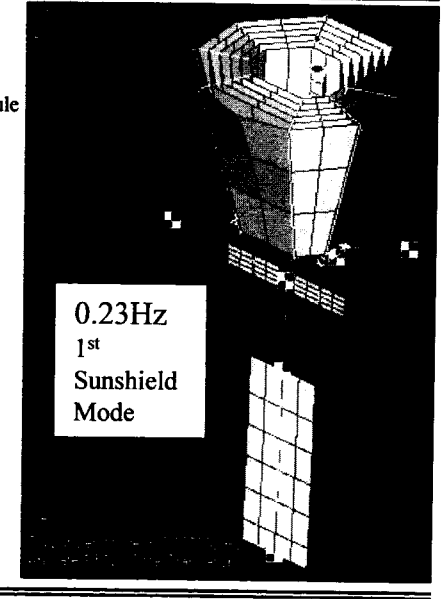


6 Free-Free Rigid Body Modes (< 1.0e-4Hz)









Mode	System	Payload	Support Module
1	5.2552e-005	6.7124e-005	4.4832e-005
2	3.4572e-005	4.3062e-005	3.1098e-005
3	2.1118e-005	3.3740e-005	1.4451e-005
4	1.9869e-005	1.7244e-005	7.2218e-006
5	2.8479e-005	4.0730e-005	1.4759e-005
6	4.8468e-005	6.0195e-005	1.7737e-005
7	8.7258e-002	7.8800e+000	8.7309e-002
8	1.6865e-001	1.3333e+001	1.7006e-001
9	2.2733e-001	1.3407e+001	2.2776e-001
10	2.3484e-001	1.5830e+001	2.4220e-001

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Secondary Tower – AMS Bending Modes

Primary Mirror Bending Modes

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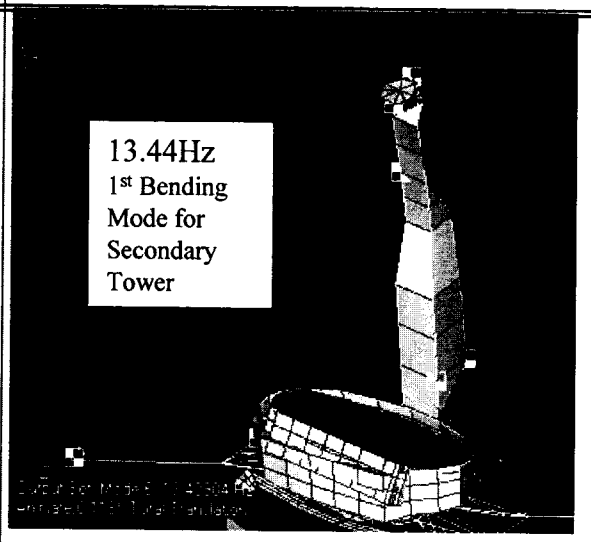

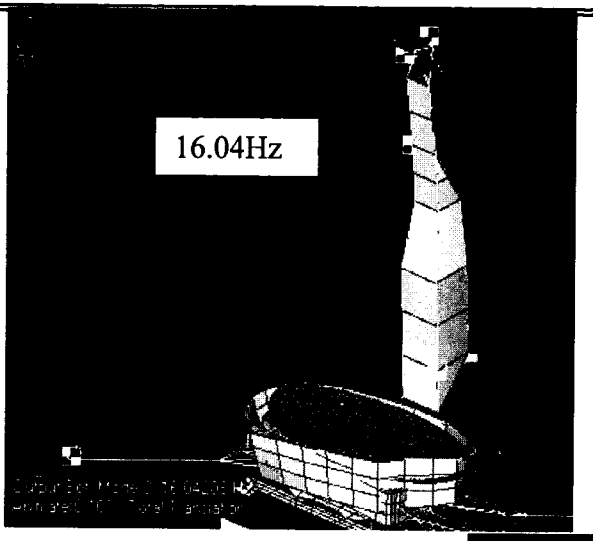

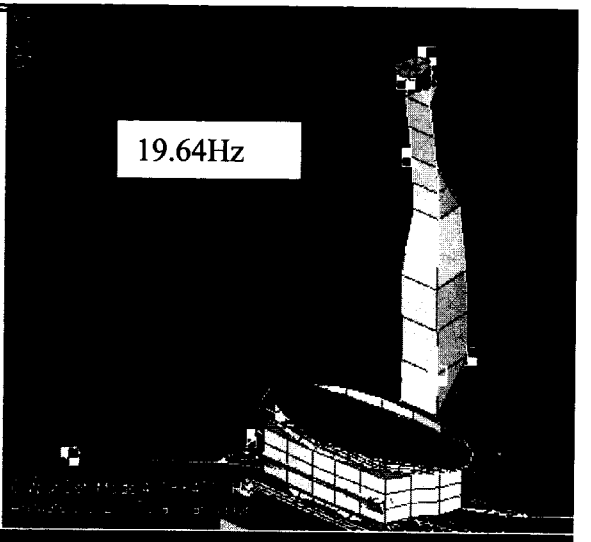

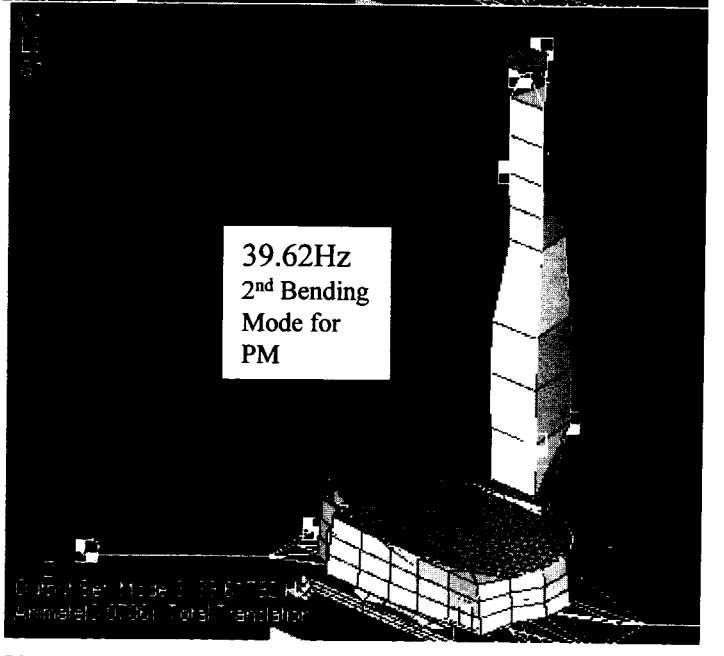

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Thermal Distortion Analysis

Primary Mirror Steady-State Temperature Results for Two 20 deg Dither Cases (80 to 100 & 170 to 190)

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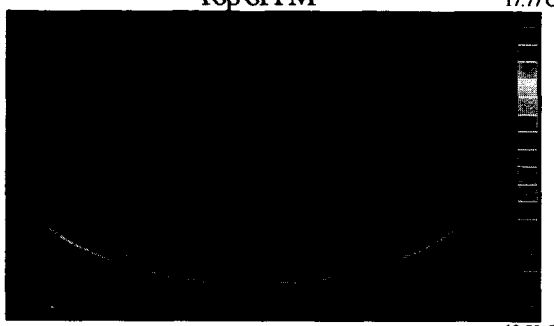
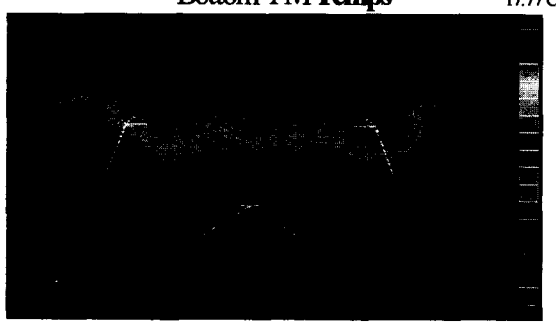
Temperature (C) Distribution for all Sun Angles (variations<mC)

4 C p-v

Top of PM



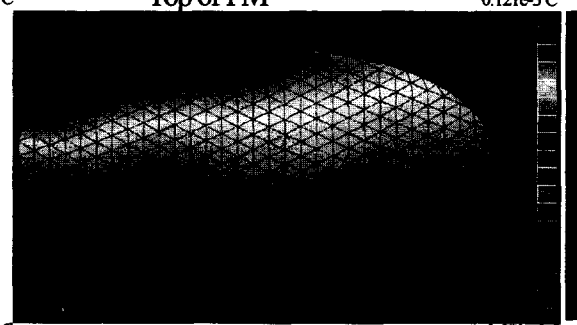
Bottom PM **Temps**



Delta Temperature (C) for Dither from 80 to 100 deg

0.69 mC p-v

Top of PM

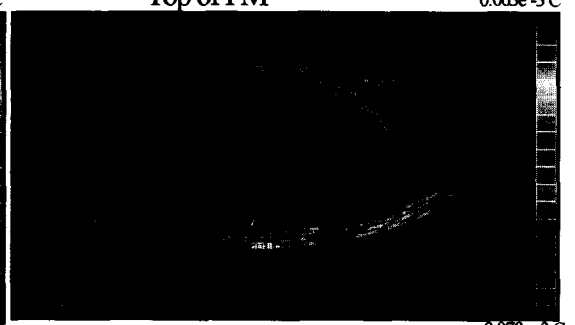


Bottom of PM **Delta Temps**

Delta Temperature (C) for Dither from 170 to 190 deg

0.14 mC p-v

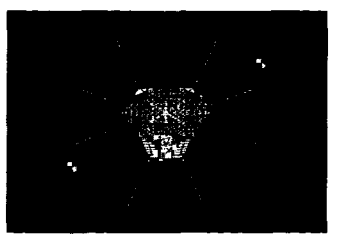
Top of PM



Bottom of PM **Delta Temps**

100 deg

80 deg



170 deg

190 deg

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Primary Mirror Steady-State Results for Two 20 deg Dither Cases (80 to 100 & 170 to 190)

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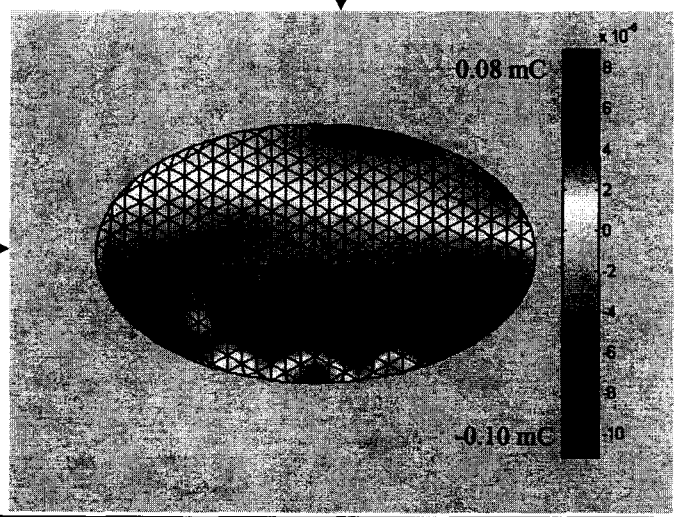
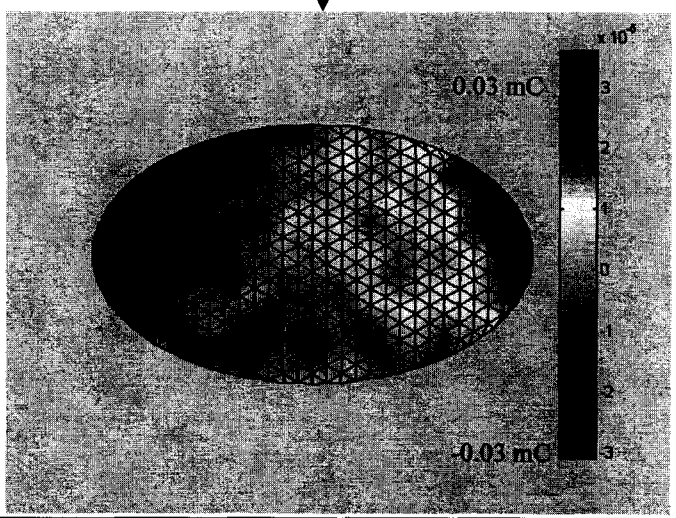
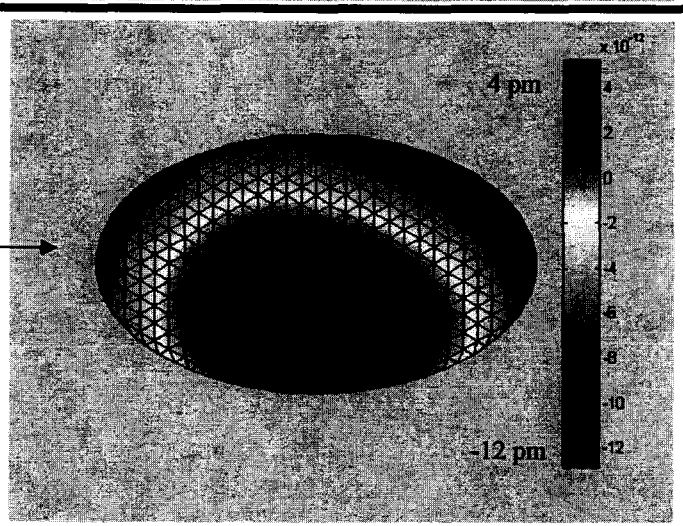
Dither from 80 to 100 deg | **Dither from 170 to 190 deg**

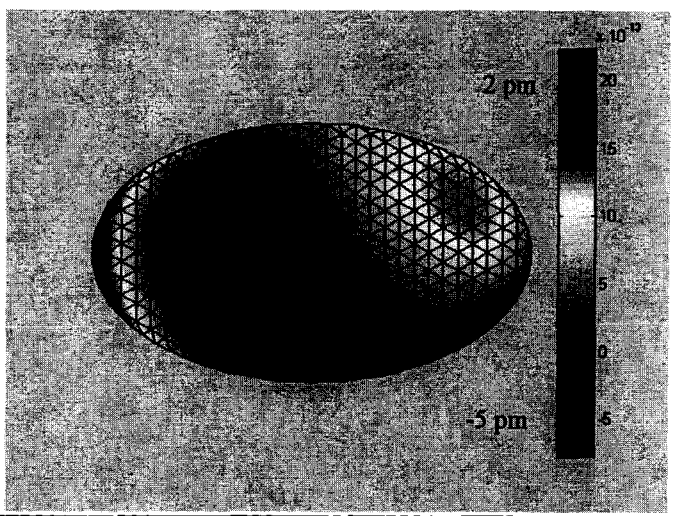
Back Surface Delta T minus Front Delta T





Front Surface Displacement Using Uniform CTE of 30ppb/C





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PM Transient Delta Temperature Response for 20 deg Dither from 170 to 190 deg orient

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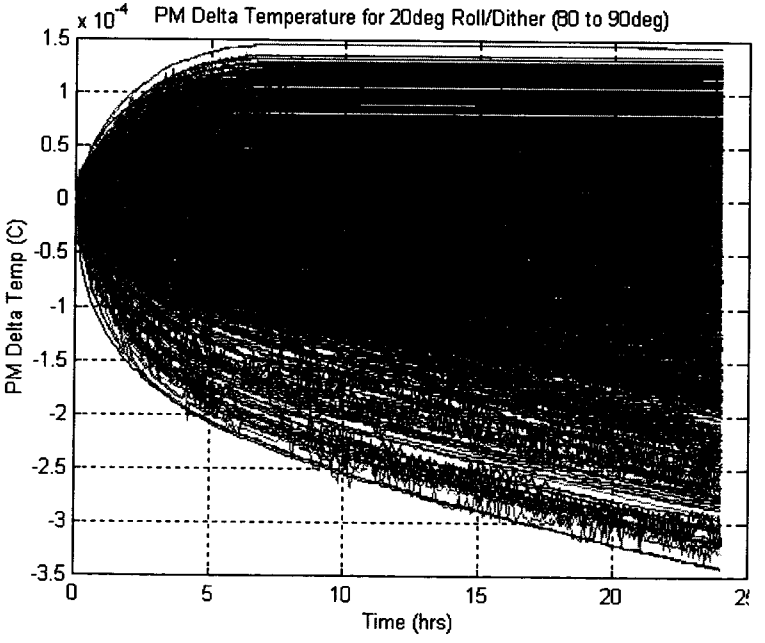
Transient Temperatures for All Primary Mirror FEM Nodes

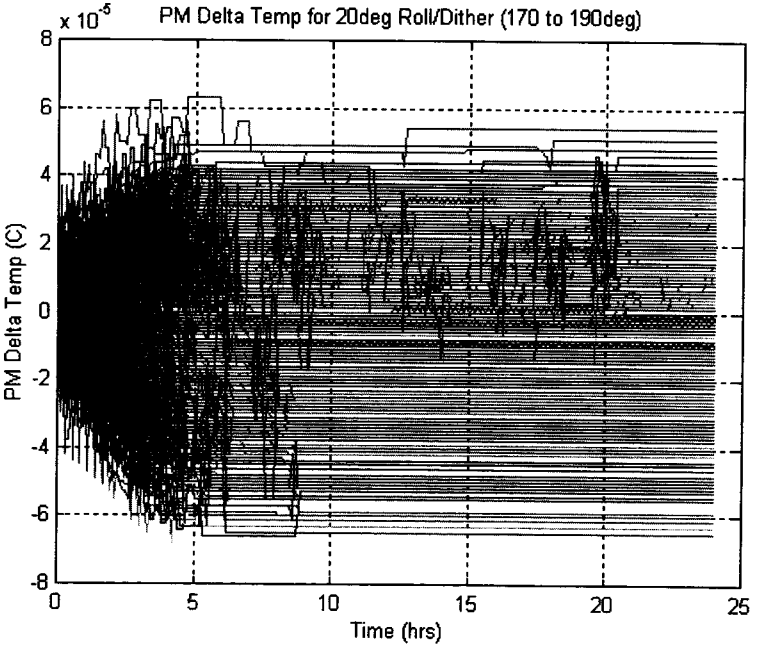
Dither from 80 to 100 deg

0.15 mC



Dither from 170 to 190 deg

0.08 mC



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WFE from Primary Mirror Distortion

Used Mid-Fidelity Primary Mirror Model
with IMOS in MATLAB environment

Following Cases Investigated:

- Uniform CTE
- Variable CTE

PM WFE Response to Thermal Transient for 20 deg Dither from 80 to 100 deg Sun Angle (Using Uniform CTE of 30ppb, 3Lam/D Reqs)

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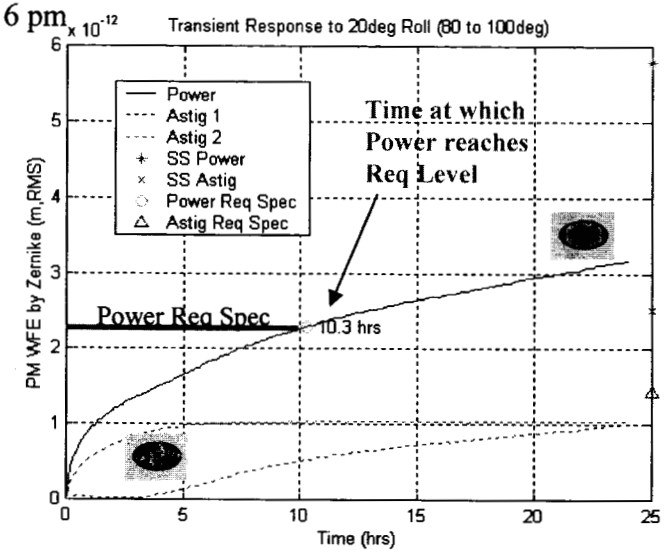
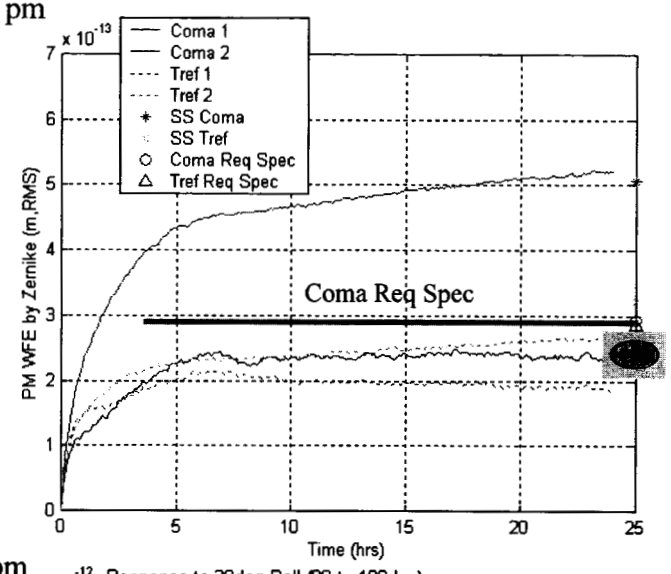
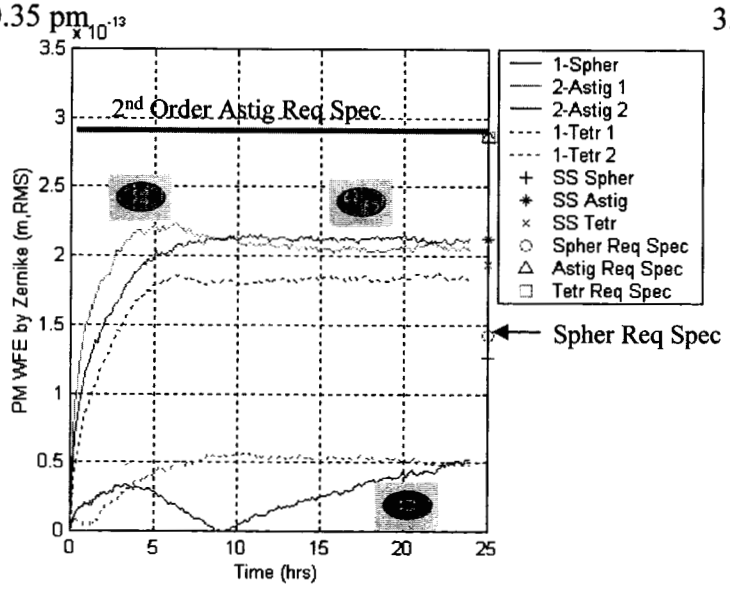
6 pm



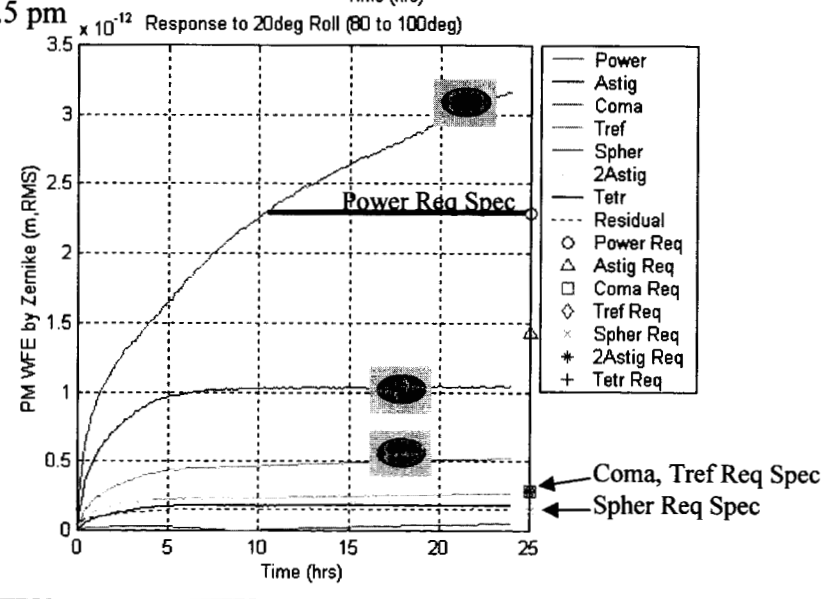
0.7 pm



0.35 pm



3.5 pm



PM WFE Response to Thermal Transient for 20 deg Dither from **170 to 190** deg Sun Angle (Using Uniform CTE of 30ppb, 3Lam/D Reqs)

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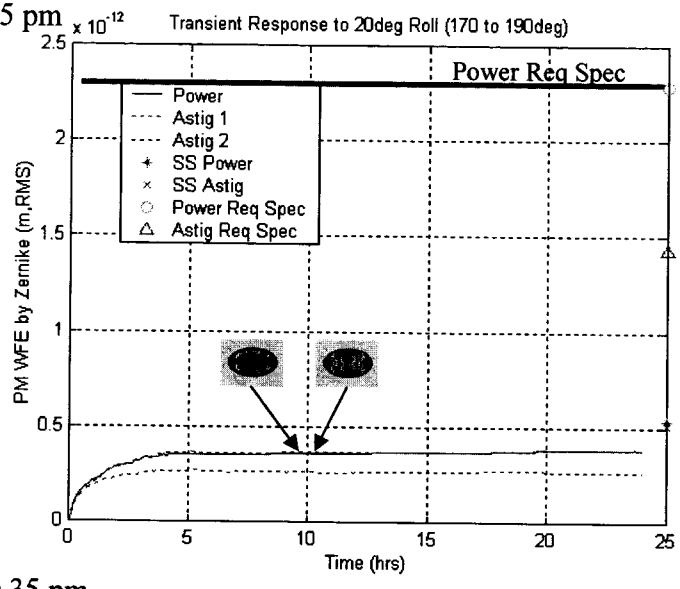
2.5 pm



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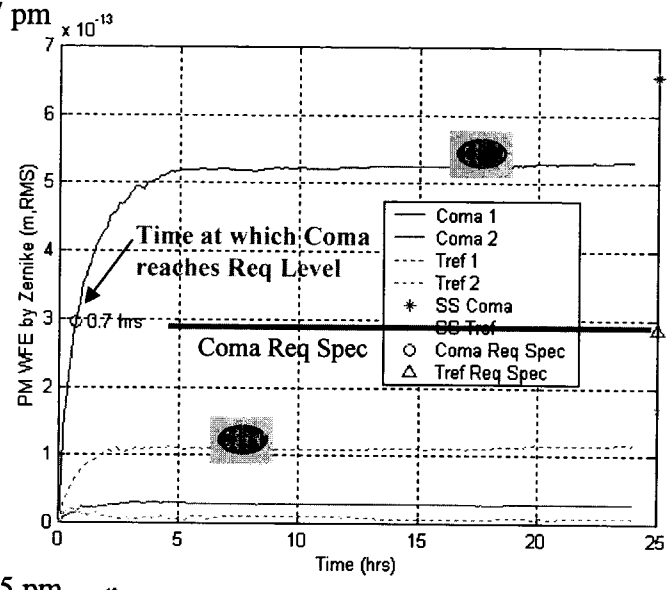
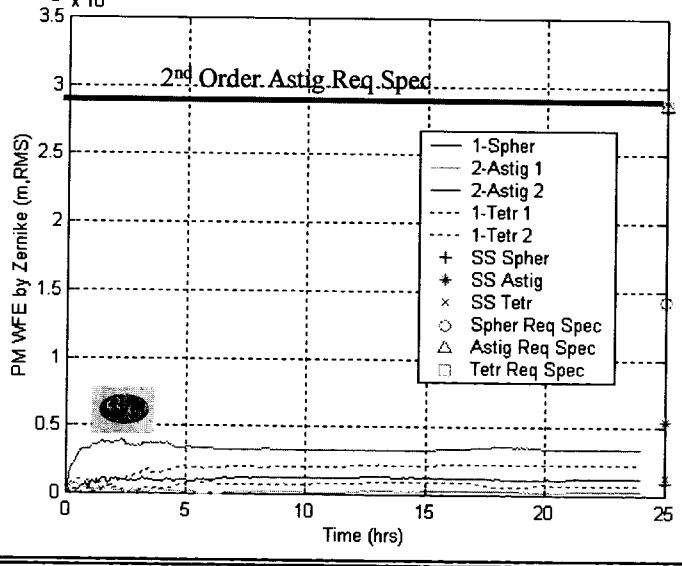
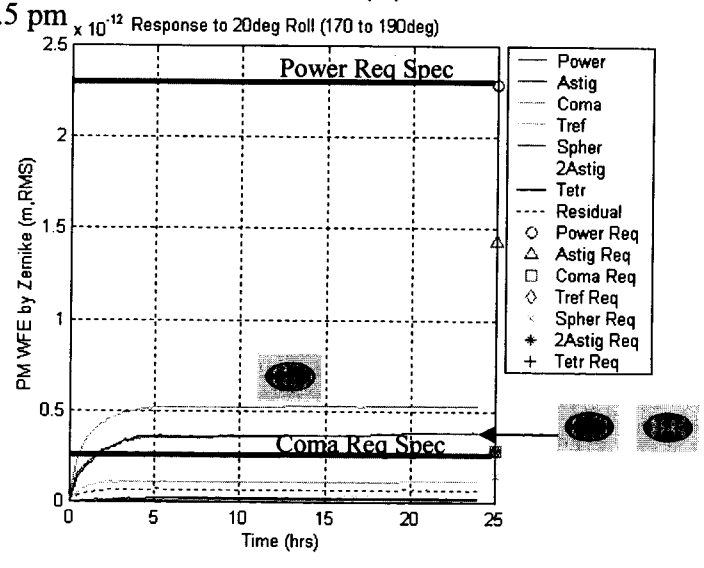


0.35 pm



2.5 pm



Monte-Carlo Study of Primary Mirror CTE Variation

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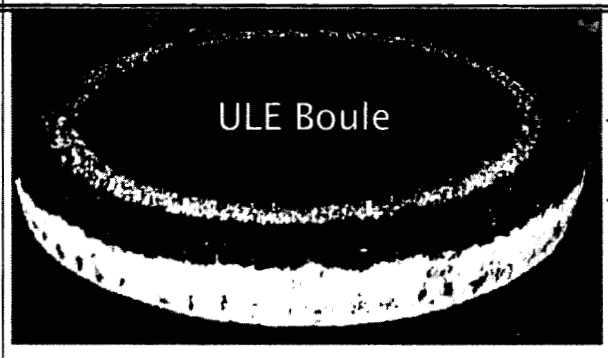
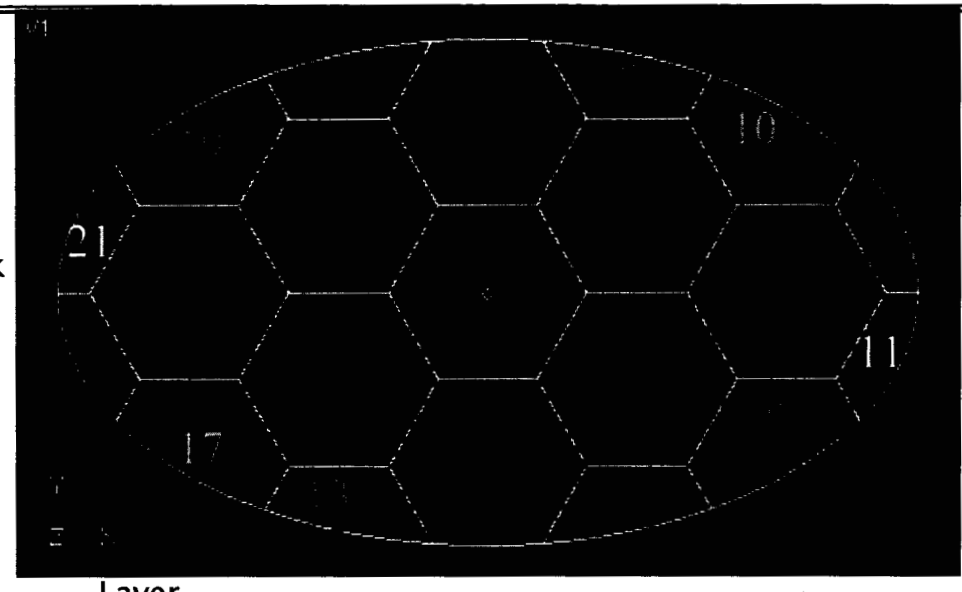
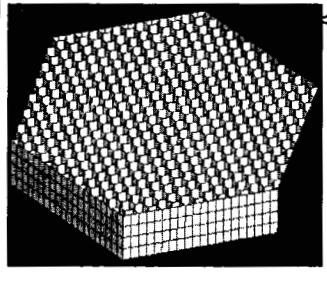


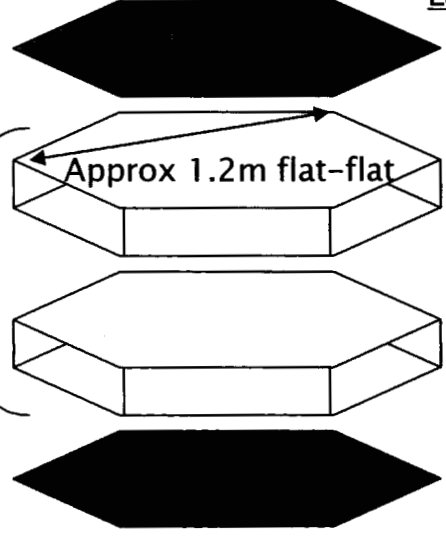
Approx 0.15m thk

Approx 1.5m dia



Core Segment:
Two Stacked, Sealed & Fused Boules





- **CTE is varied by region**
- **There are 84 regions**
  - 4 layers x 21 segments
- **CTE variation functions used:**
  - Bias or piston
  - Side to side variation along x & y dir
  - Radial (in xy plane)
  - Axial (along z-dir) used for core segments only

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Monte-Carlo Study of Primary Mirror CTE Variation

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- Used 1000 random CTE distributions consistent with the TDM CTE specifications
- Each of the 84 regions of the mirror were given CTE variations according to the four functions: bias, side to side, radial & axial

TDM PDR CTE Specs

(used by Kodak)

INITIAL MIRROR CTE TOLERANCES		
No.	**Description**	**Tolerance (ppb/C)**
1	Weighted Blank Average	+/- 10
2	Core Segment Axial Gradient	+/- 10
3	Core Segment Radial Range	< 15
4	Max Core Segment-Segment Average Delta	< 10
5	Face Plate Axial Gradient	+/- 5
6	Face Plates Pt-to-Pt Difference	< 5
7	(Face Plate Average) - (Core Segment Average)	+5 to +15

Parameters Used for CTE Variability Study:

dCTEdLateral = 4.15e-9; gives about 5ppb cte variation over segment

dCTEdAxial = 1.60e-7; gives about 10ppb cte variation

dCTEdRad_Fac = 8.30e-9; gives about 5ppb cte variation for facesheets

dCTEdRad_Cor = 2.50e-8; gives about 15ppb cte variation for core

dCTEbias_Fac= 1.50e-8; gives about 15ppb cte variation for facesheets

dCTEbias_Cor= 1.50e-8; gives about 15ppb cte variation for core

dCTEbias_Fac2= 5.0e-9; front/back matching within 5ppb

Monte-Carlo Study of Primary Mirror CTE Variation

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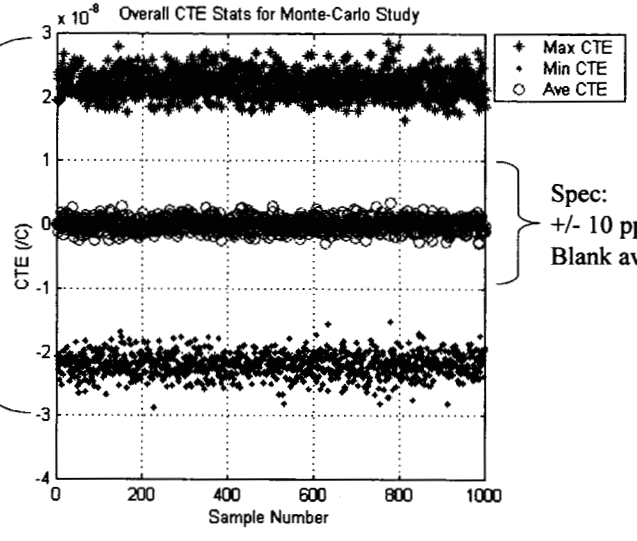
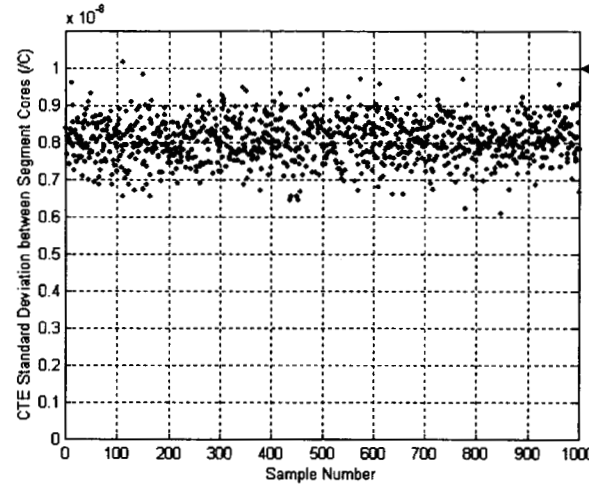
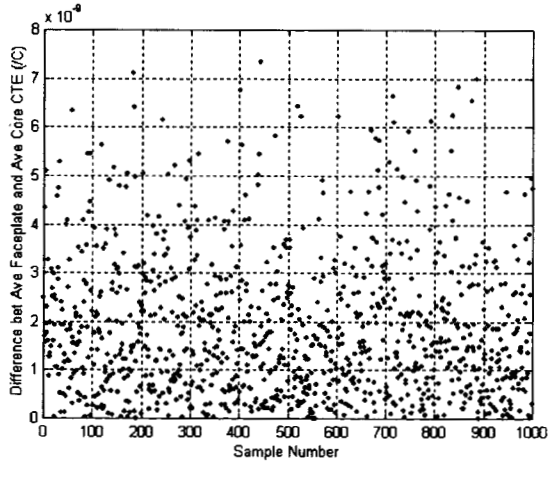
+/- 30 ppb Max/min overall

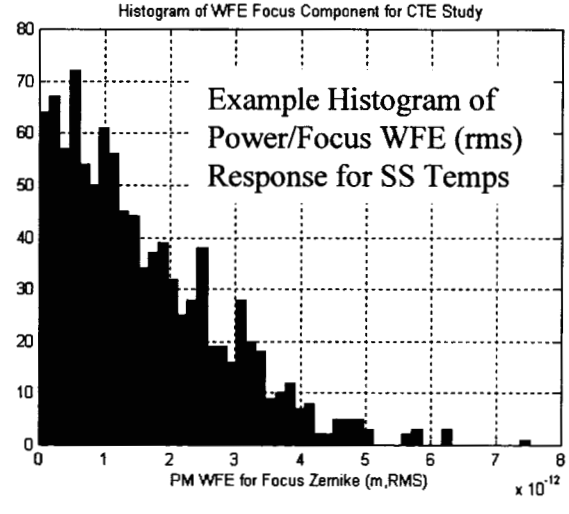


Spec: +/- 10 ppb Blank ave



Spec: Ave cte diff bet core segs <10 ppb





Results using **steady-state** temperatures for 20 deg roll

Monte-Carlo Study of PM WFE Response to CTE Variation for Two Steady-State 20 deg Dither Cases

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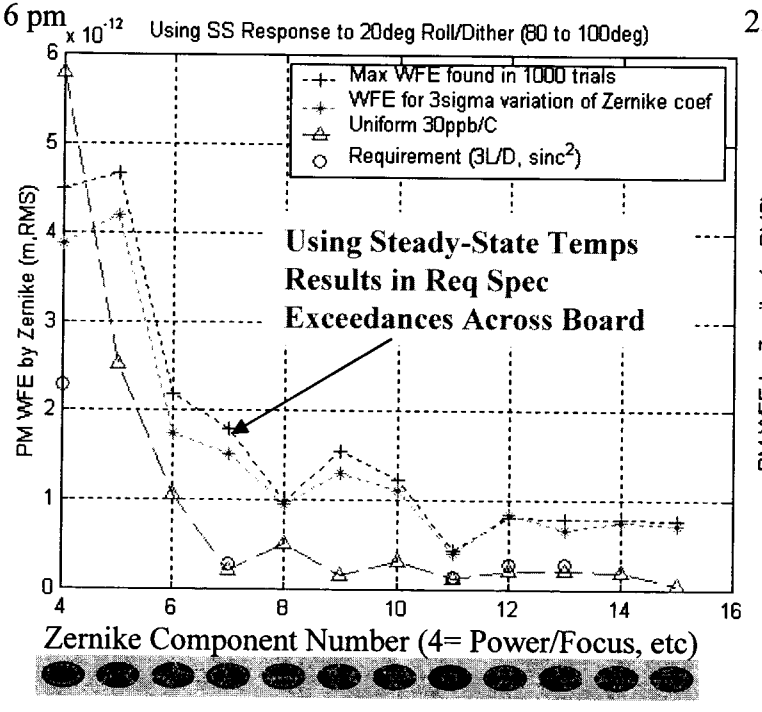
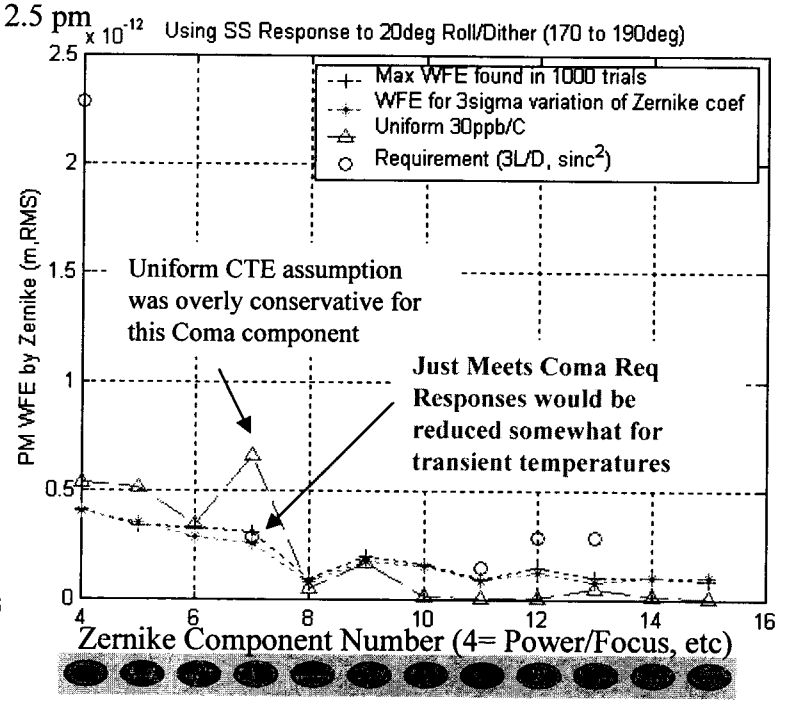
Dither from 80 to 100 deg



Dither from 170 to 190 deg



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Using Steady-State Temps is Too Conservative for 80 to 100 deg Case

Same 1000 Random CTE Distributions Used for Both Cases

Monte-Carlo Study of PM WFE Response to CTE Variation for Transient & SS Thermal Response

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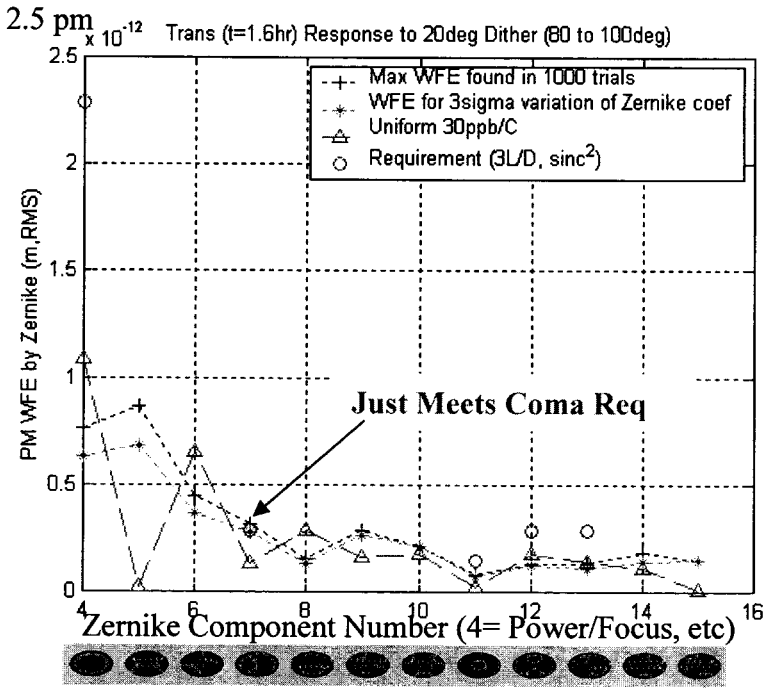
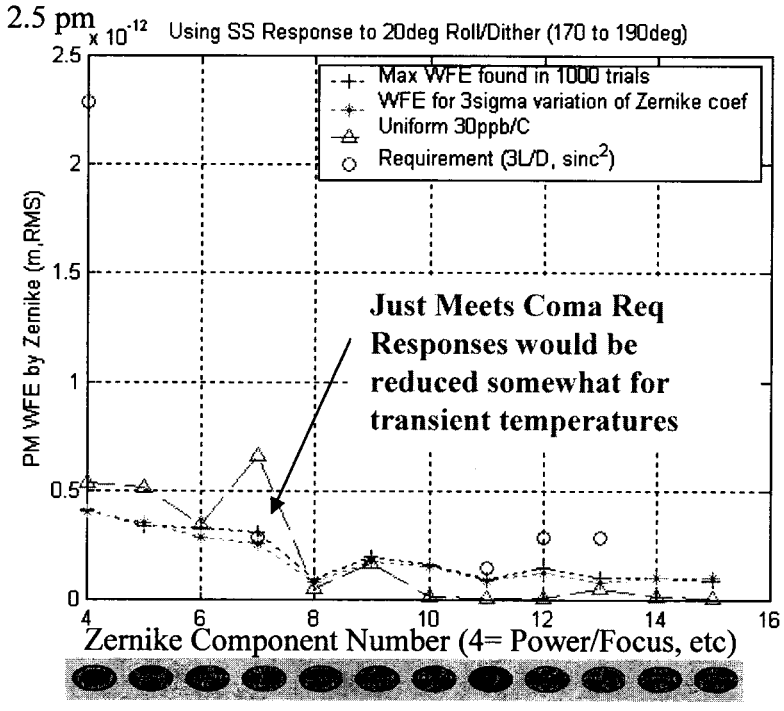
Using **Transient** Temps at **1.6hrs** After Dither from **80 to 100** deg



Using **Steady-State** Temps for Dither from **170 to 190** deg



Same 1000 Random CTE Distributions Used for Both Cases

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Optimization Process for Primary Mirror Segment Placement

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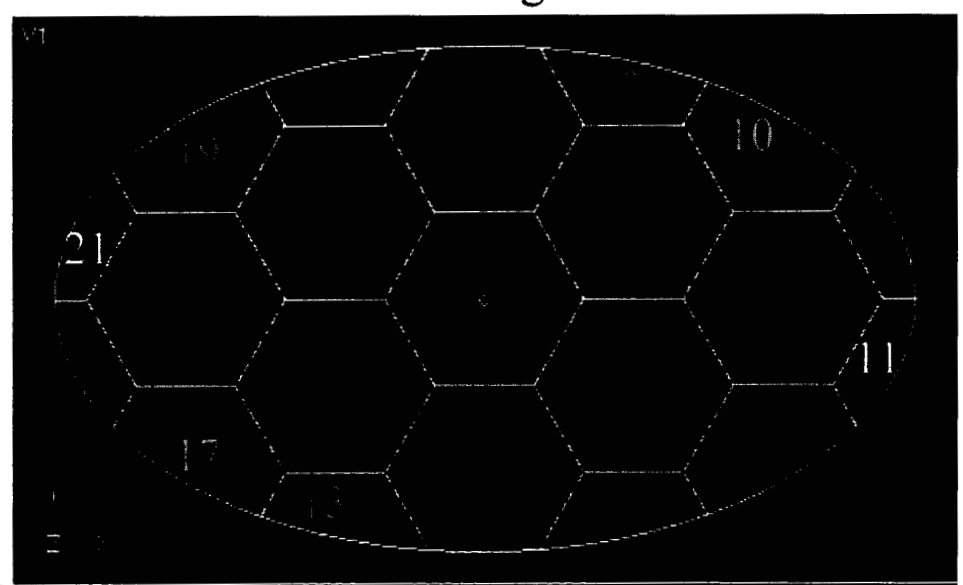
- Segments CTEs can be measured (to <0.5ppb) prior to mirror assembly
- Can estimate worst-case thermal loading from analysis
- Positions of 9 similar full-size PM segments are shuffled
- Positions of 12 remaining segments are shuffled in pairs

  Each of the partial segments has two possible positions in the blank

  (Not 4 because of different front & back face-sheet thicknesses)
- Find optimal (min WFE) placement combo for measured segment CTEs

- Similar approach of optimal glass placement based on measured CTEs has been used successfully for SUBARU and GEMINI mirrors (>8m dia)



Optimization of Primary Mirror Segment Placement Using **Steady-State** Temperatures

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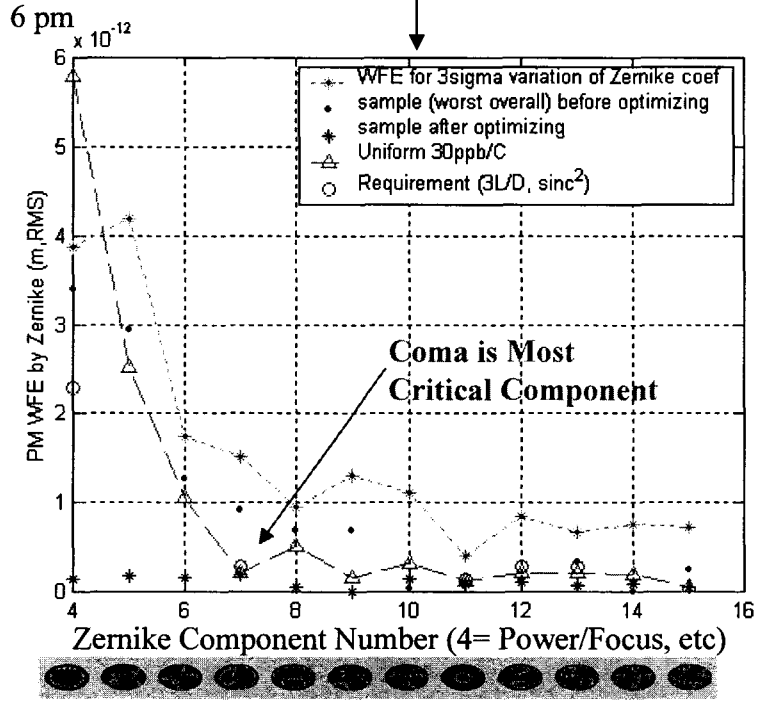
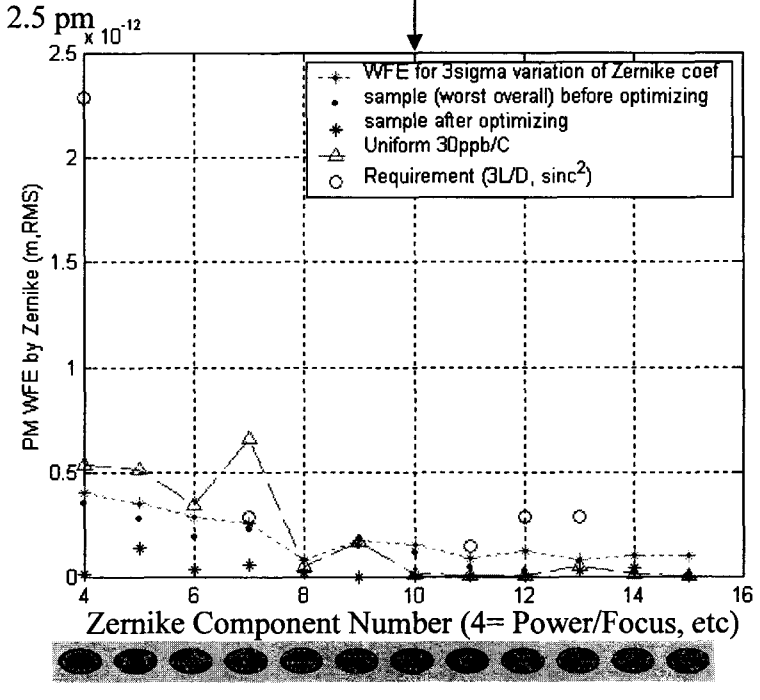
Using **Steady-State** Temps for Dither from **80 to 100** deg



Using **Steady-State** Temps for Dither from **170 to 190** deg

Using optimal segment placement from 80 to 100 deg case



Optimization of Segment Positioning Can Reduce WFE Significantly

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Optimization of Primary Mirror Segment Placement

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Summary for PM Design with **Non-Optimized** Segment Placement

	80 to 100 deg Dither			
Zernike	Stead-State	Trans @ 1.6hrs	3L/D Req	Ratio
Comp	Resp (pm)	Resp (pm)	Specs (pm)	Req/Trans
[redacted]	4.49	0.76	2.29	3.00
[redacted]	1.80	0.29	0.29	1.00
[redacted]	0.45	0.08	0.14	1.85
[redacted]	0.81	0.13	0.29	2.13
[redacted]	0.78	0.13	0.29	2.18

Note: only transient response meets reqs, and only for 1.6 hrs for non-optimized segment placement

Summary for PM Design with **Optimized** Segment Placement Based on 80 to 100 deg Dither

	80 to 100 deg Dither		
Zernike	Stead-State	3L/D Req	Ratio
Comp	Resp (pm)	Specs (pm)	Req/Resp
[redacted]	0.14	2.29	16.21
[redacted]	0.19	0.29	1.47
[redacted]	0.09	0.14	1.64
[redacted]	0.11	0.29	2.53
[redacted]	0.07	0.29	3.86

Results for 170 to 190 deg Dither Using **Optimized** Segment Placement Based on 80 to 100 deg Dither

	170 to 190 deg Dither		
Zernike	Stead-State	3L/D Req	Ratio
Comp	Resp (pm)	Specs (pm)	Req/Resp
[redacted]	0.02	2.29	126.52
[redacted]	0.06	0.29	4.88
[redacted]	0.01	0.14	22.70
[redacted]	0.01	0.29	40.28
[redacted]	0.03	0.29	9.93

Note: The results for PM with optimal segment placement are **steady-state** (conservative for dither)

Telescope Steady-State Temperature Results for Two 20 deg Dither Cases (80 to 100 & 170 to 190)

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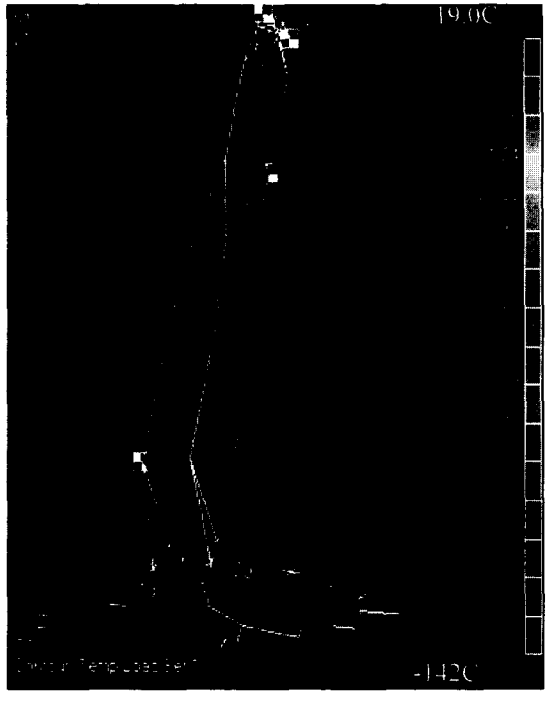
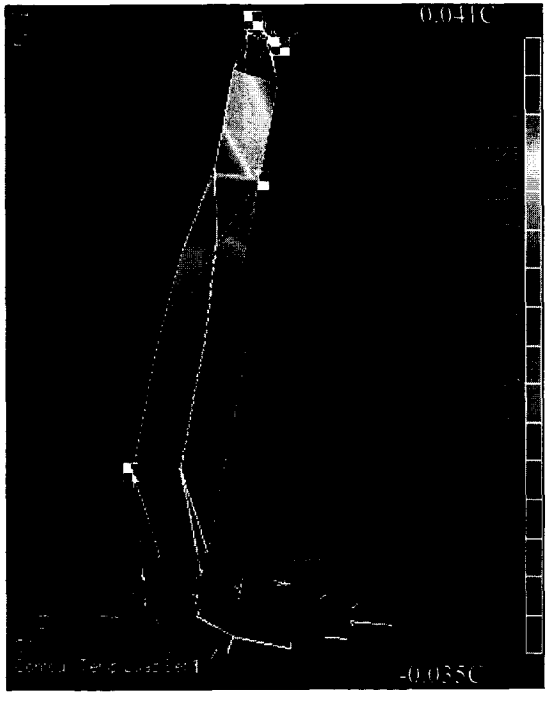
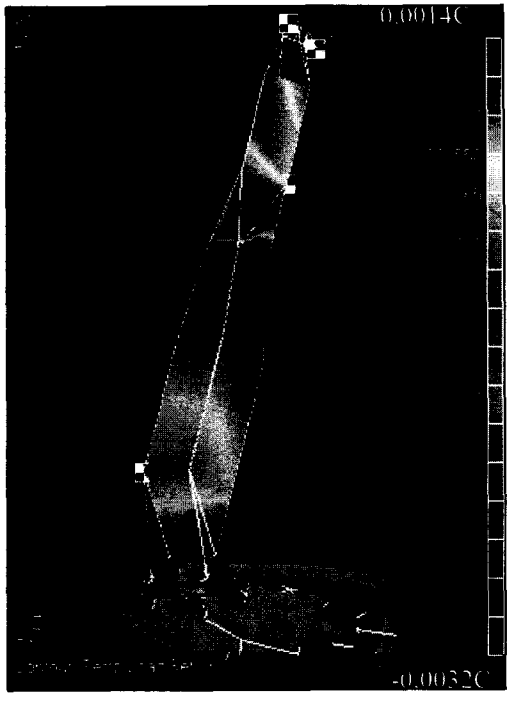
Temperature (C) Distribution for **all Sun Angles** (variations<mC)



Delta Temperature (C) for Dither from **80 to 100 deg**

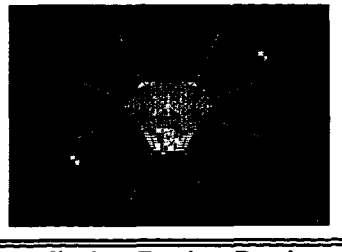


Delta Temperature (C) for Dither from **170 to 190 deg**



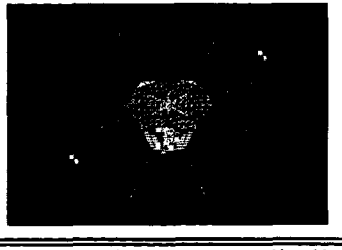
100 deg

80 deg



170 deg

190 deg



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Primary & Secondary Mirrors Response to Thermal Transient for 20 deg Dither from 80 to 100 deg Sun Angle

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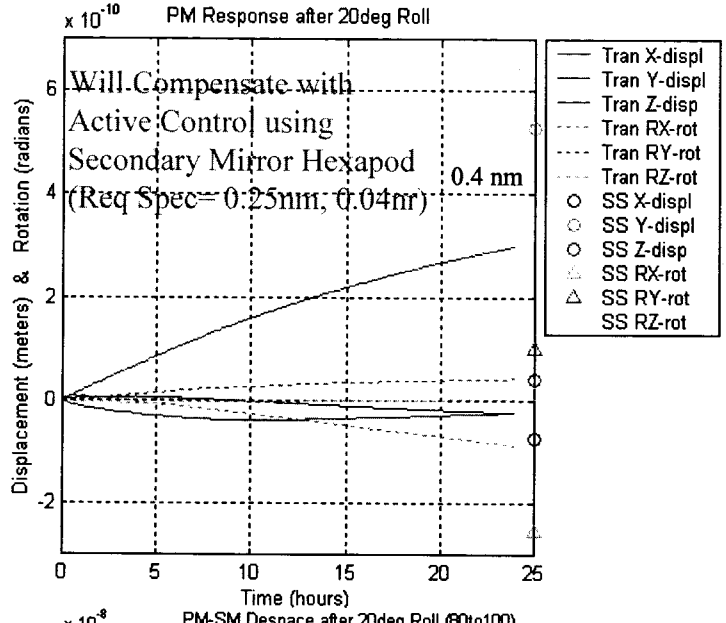

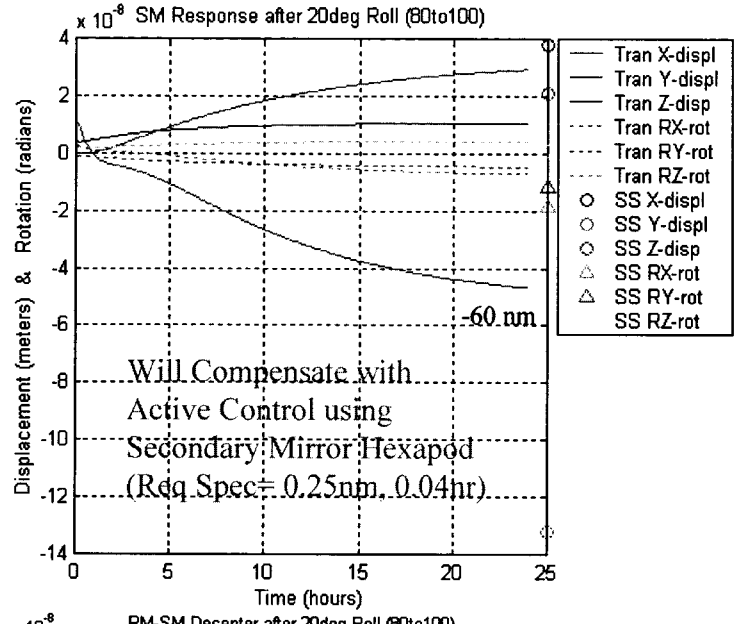

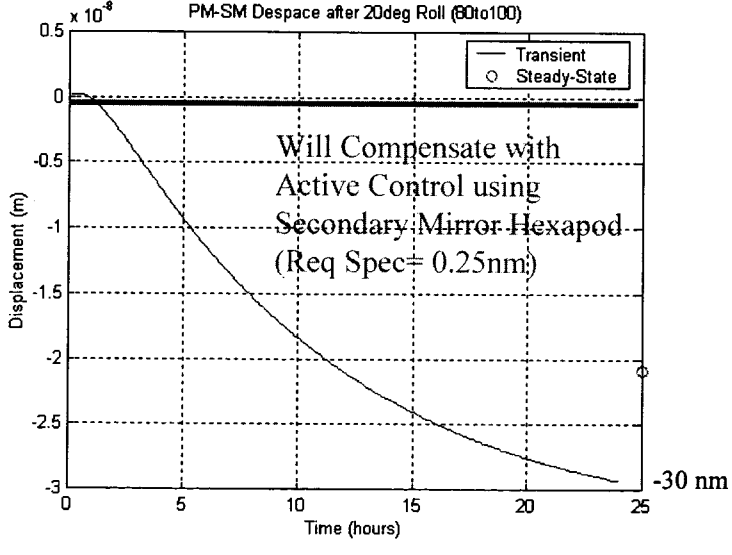

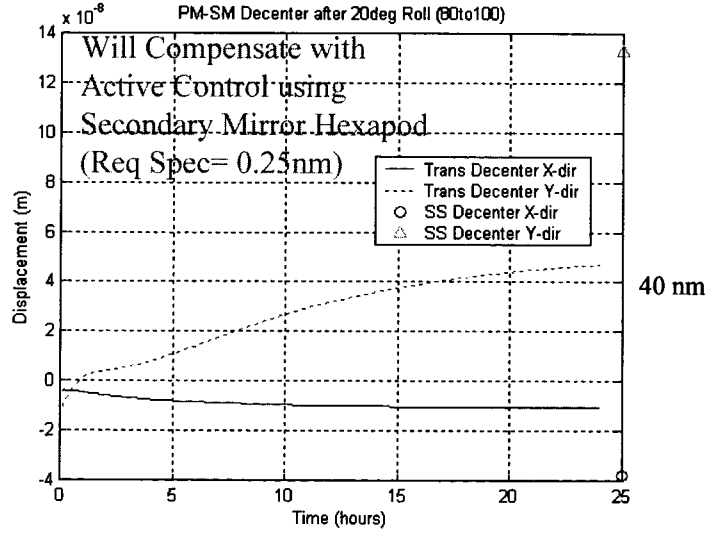

Primary & Secondary Mirrors Response to Thermal Transient for 20 deg Dither from 170 to 190 deg Sun Angle

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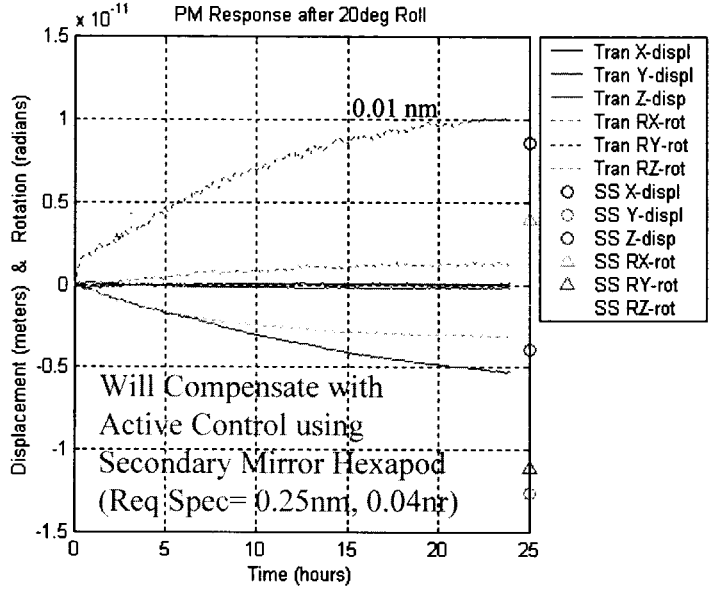

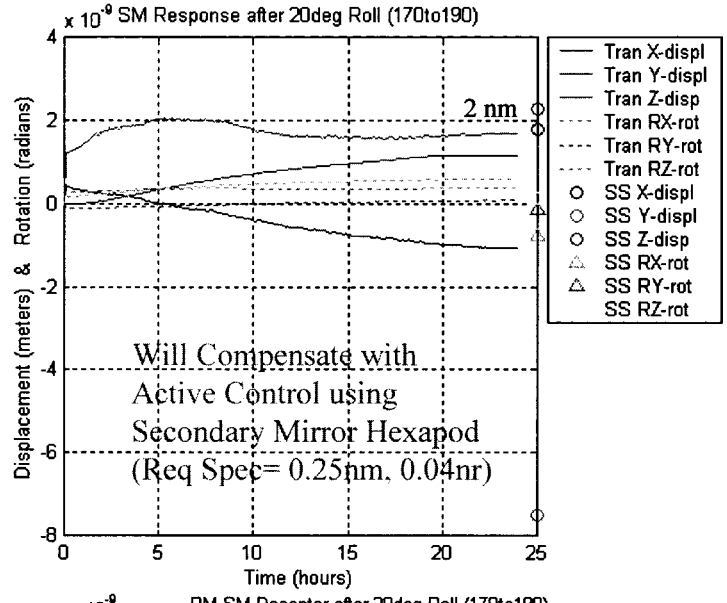

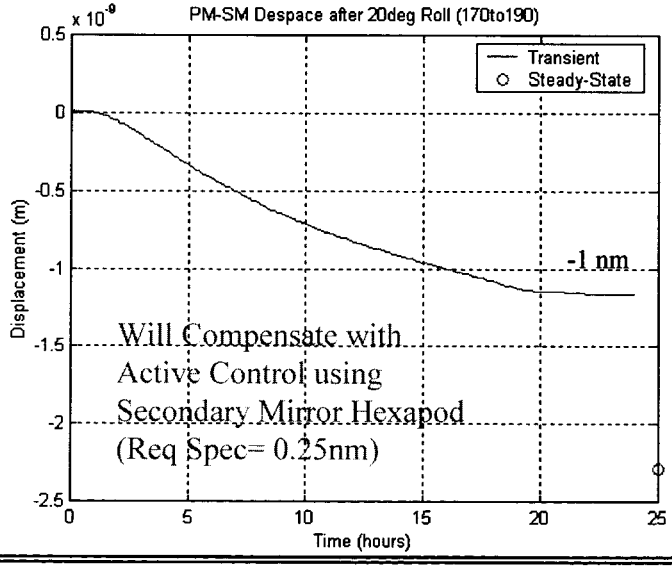

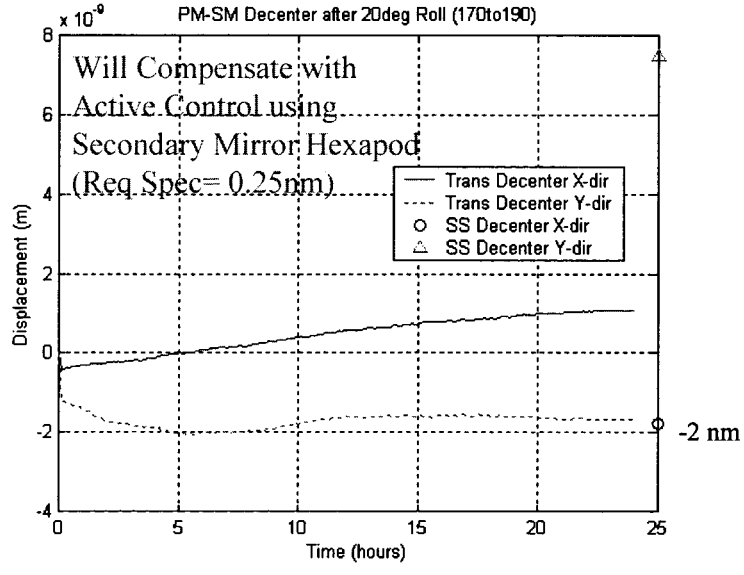

Conclusions:

1. Of the two orthogonal 20 deg dither maneuvers studied (80 to 100 deg & 170 to 190 deg), the 80 to 100 deg results in larger primary mirror low order Zernike aberrations.
2. For the 80 to 90 deg dither case, the uniform cte assumption produces non-conservative results, such that cte variability must be considered to properly evaluate performance.
3. The primary mirror response to the 80 to 100 deg dither meets requirement specs for 1.6 hours of transient response after the maneuver, with coma being the worst of the critical aberration components, and does not meet requirement specs for the conservative steady-state response for the non-optimized pm segment placement.
4. For the optimized segment placement, based on the 80 to 100 deg dither, the response meets requirement specs for the thermal steady-state and transient cases.
5. The primary mirror response to the 170 to 190 deg dither meets requirement specs for the thermal steady-state and transient responses (even non-optimized).
6. Results are encouraging, but additional margin for the non-optimized segment placement configuration would be good at this design stage

Future Work:

1. Re-design the AMS/Secondary tower bracket isolation such that all isolation struts have the same length
2. The sunshield v-groove membrane geometry will be re-designed to circularize the shape near the outboard end
3. Look at more realistic roll/dither scenarios, including proper time sequencing of events.
4. Complete design of launch support equipment, & perform launch loads analysis
5. Account for joints in model & perform mico-dynamics (joint-slip) analysis
6. Investigate lighter weight construction design options for the ULE primary mirror (larger cell size with cathedral ribs in face-sheets)
7. Investigate different materials, as well as associated construction designs for the primary mirror
8. Reduce masses for AMS, Spacecraft truss & Secondary tower bracket, and update model to be consistent with current mass list

Back-up Charts

1G Distortion Analysis

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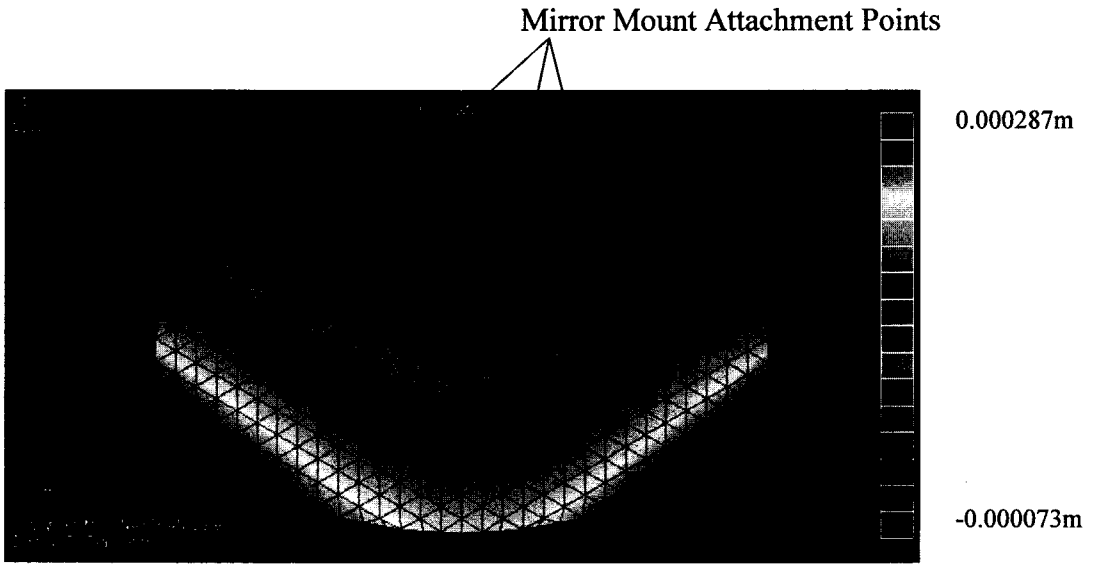

Primary Mirror Sag due to Unit Gravity in +Z-dir (basic cs)

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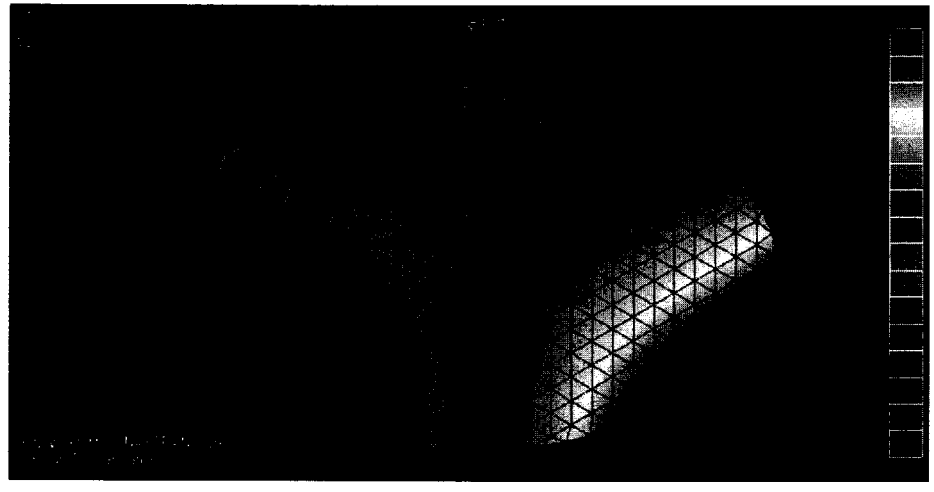
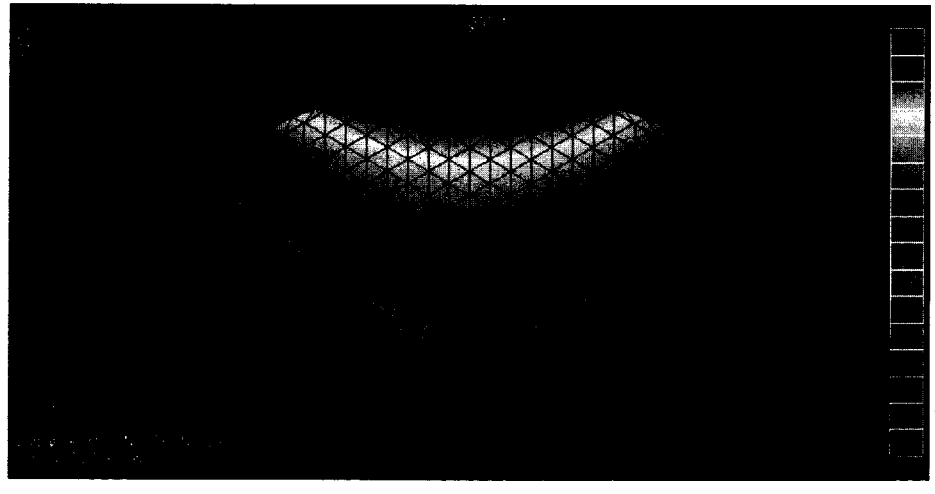


0.000068m

-0.000070m

Primary Mirror Sag due to Unit Gravity in X-dir (basic cs)



0.000089m

-0.000115m

Primary Mirror Sag due to Unit Gravity in Y-dir (basic cs)