Performance Analysis of the NGST "Yardstick" Concept via Integrated Modeling

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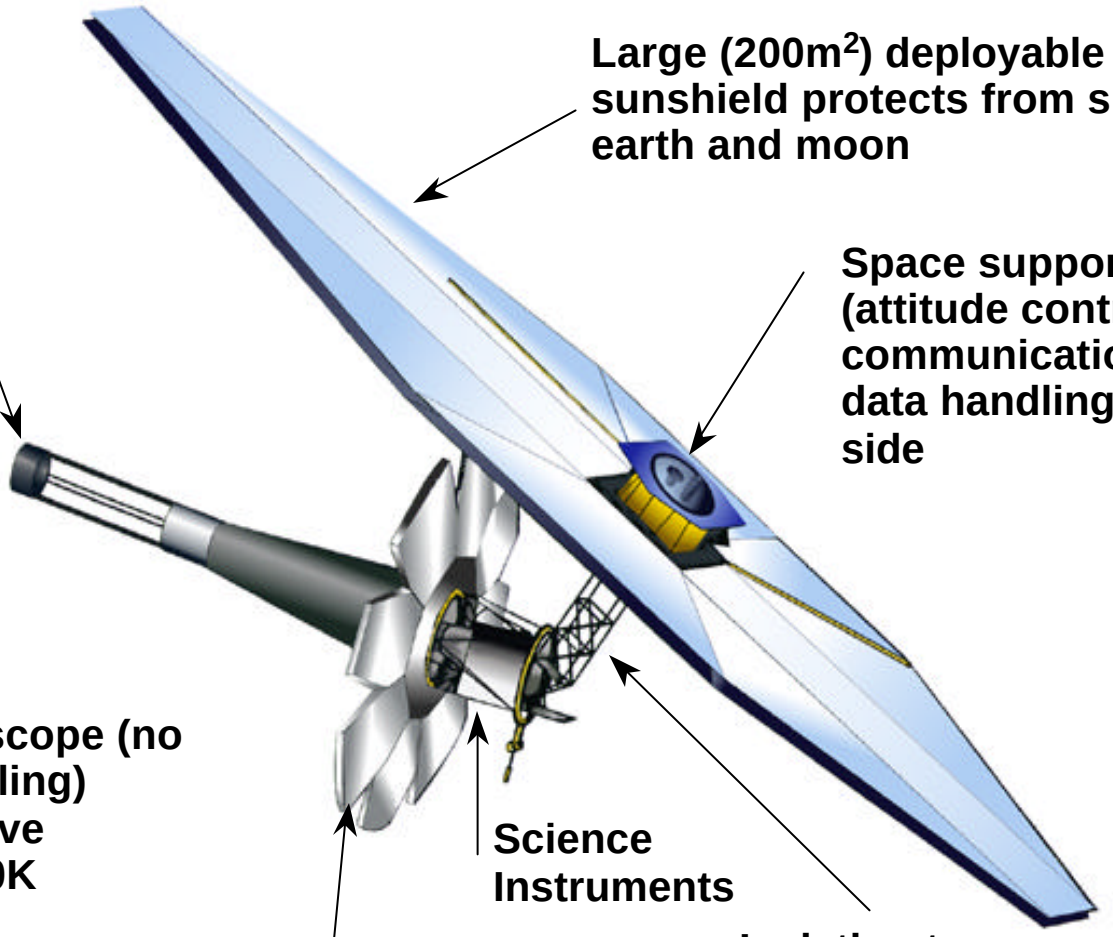
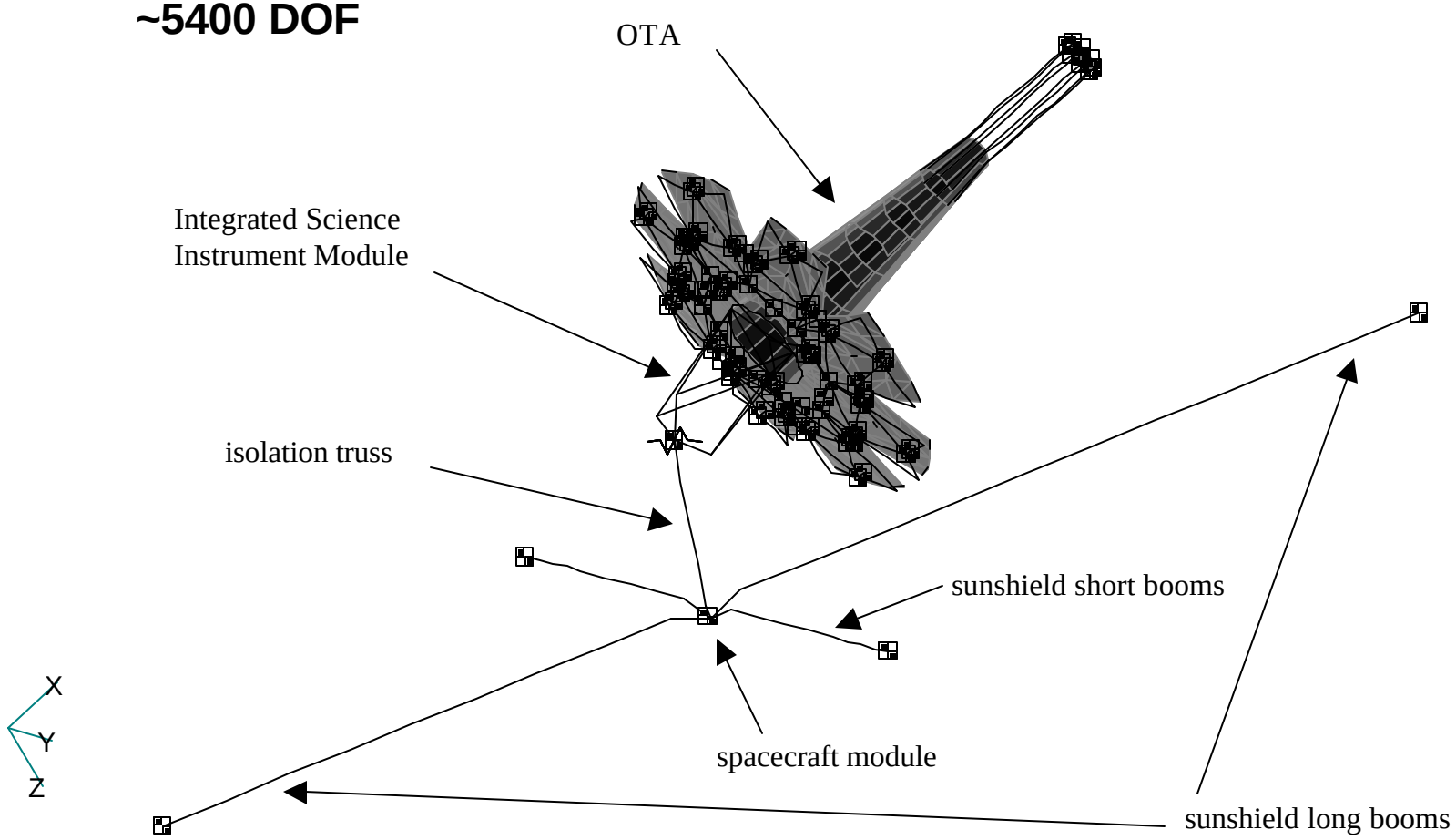
August 2000

NGST "Yardstick" Concept

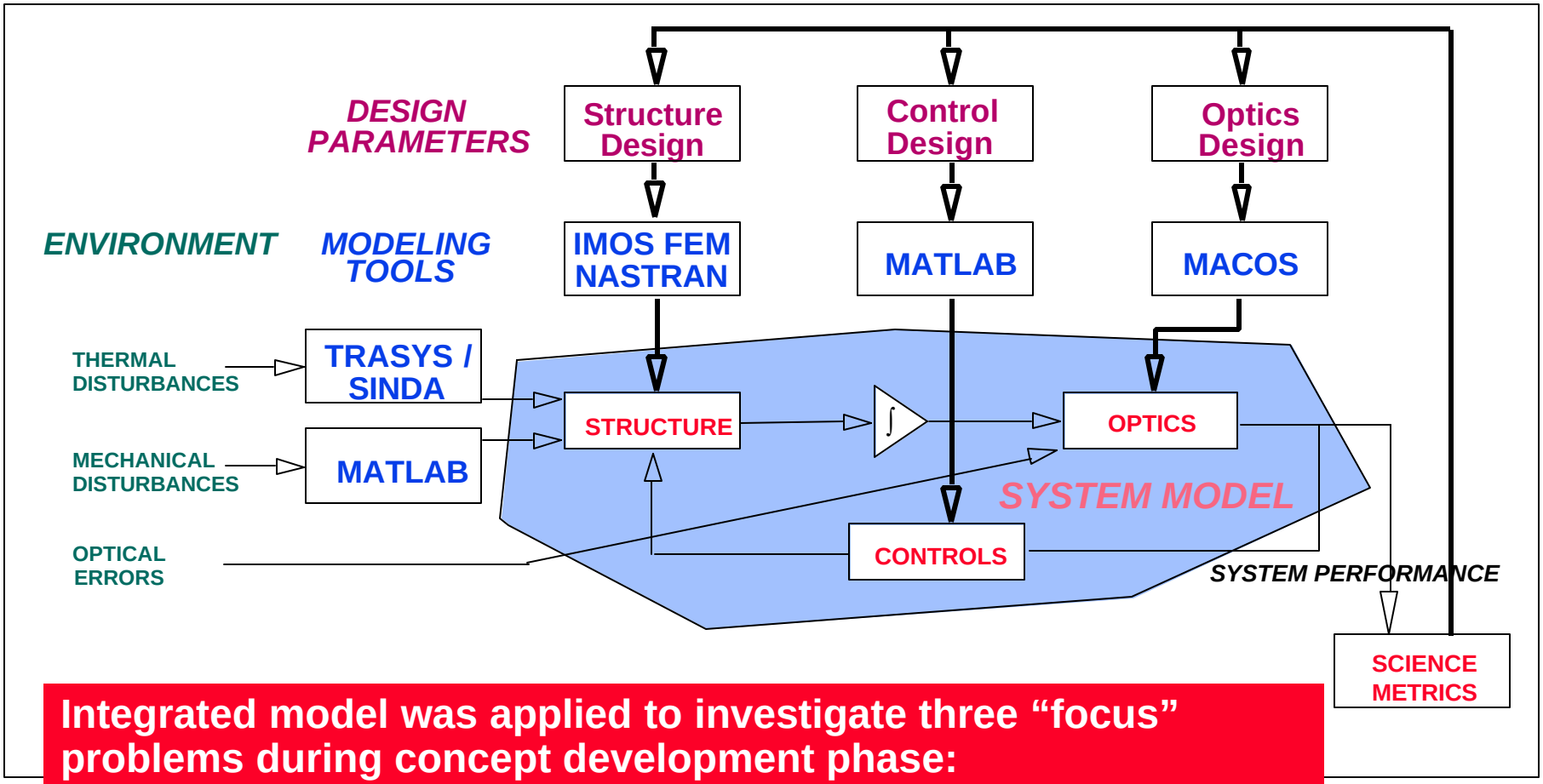


Observatory FEM

Model contains ~5400 DOF



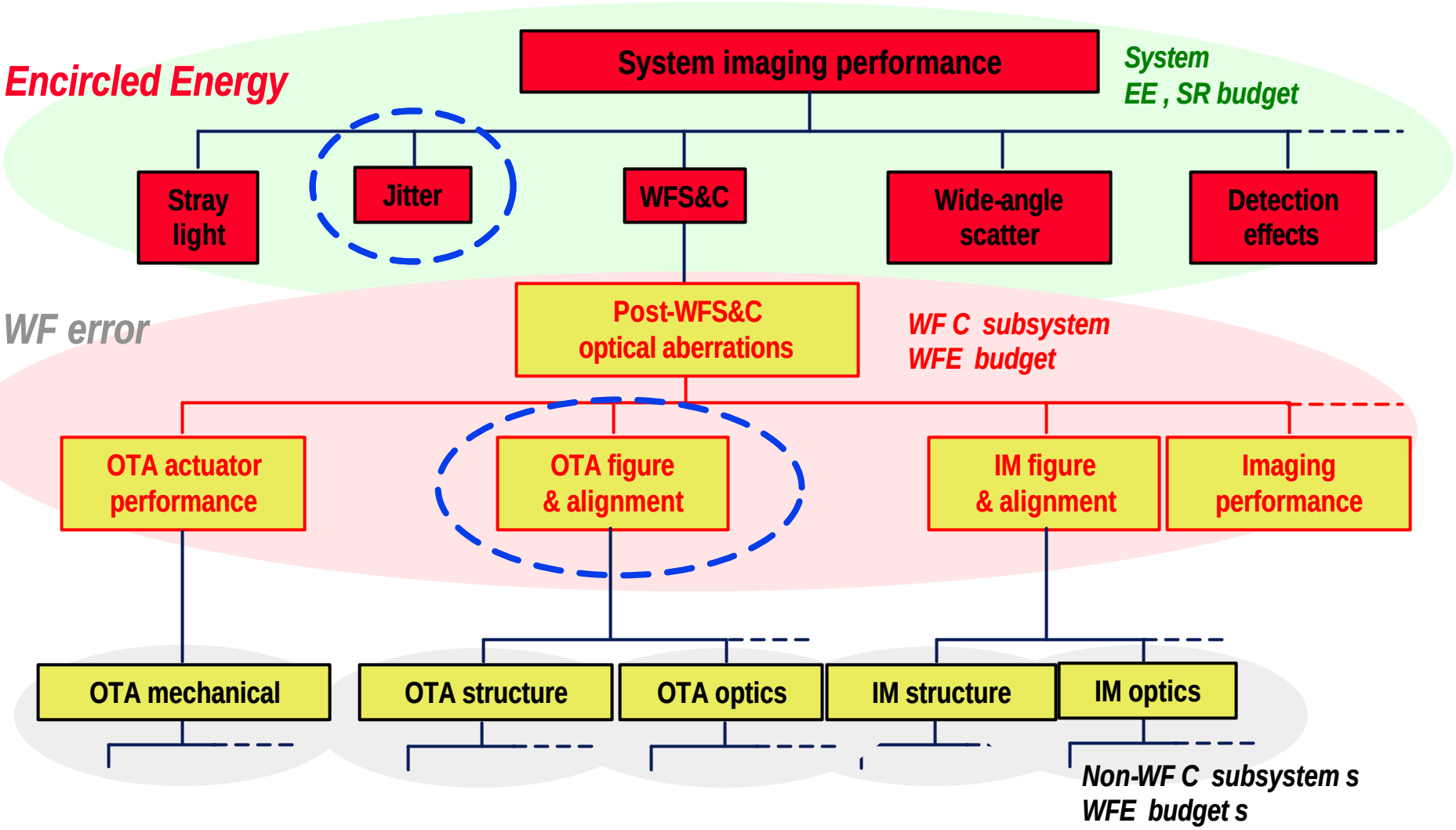
IMOS Environment



Integrated model was applied to investigate three "focus" problems during concept development phase:

- **thermal-elastic deformation of OTA**
- **line-of-sight stability (jitter)**
- **wavefront sensing and control (not really addressed here)**

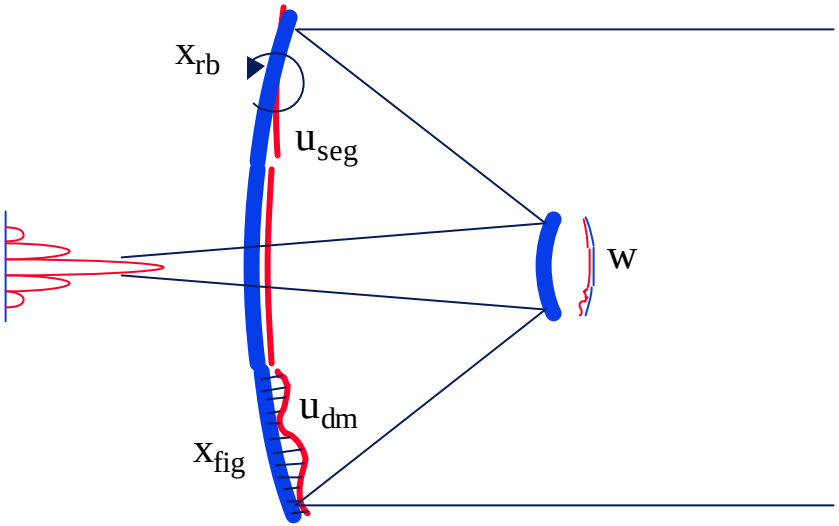
System Error Budget Overview



Thermal-Elastic Analysis

- Linear Systems Model
- Optics Model
- Thermal Model
- OTA FEM
- Results for launch-to-orbit cooldown
- Results for transient (attitude re-orientation)
- Results for transient with active thermal control

Linear Error Model for Thermal Analysis



$$x = \begin{bmatrix} x_{segrot} \\ x_{segtrans} \\ x_{IMrot} \\ x_{IMtrans} \\ x_{fig} \\ \vdots \end{bmatrix}$$

Alignment and figure states

$$w = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix}$$

Wavefront sampled at N discrete points in the exit pupil

Linear optical model

$$w_0 = C_x\, x + C_u\, u_0$$

WF sensing

$$w_{est} = w_0 + dw_{est}$$

Control

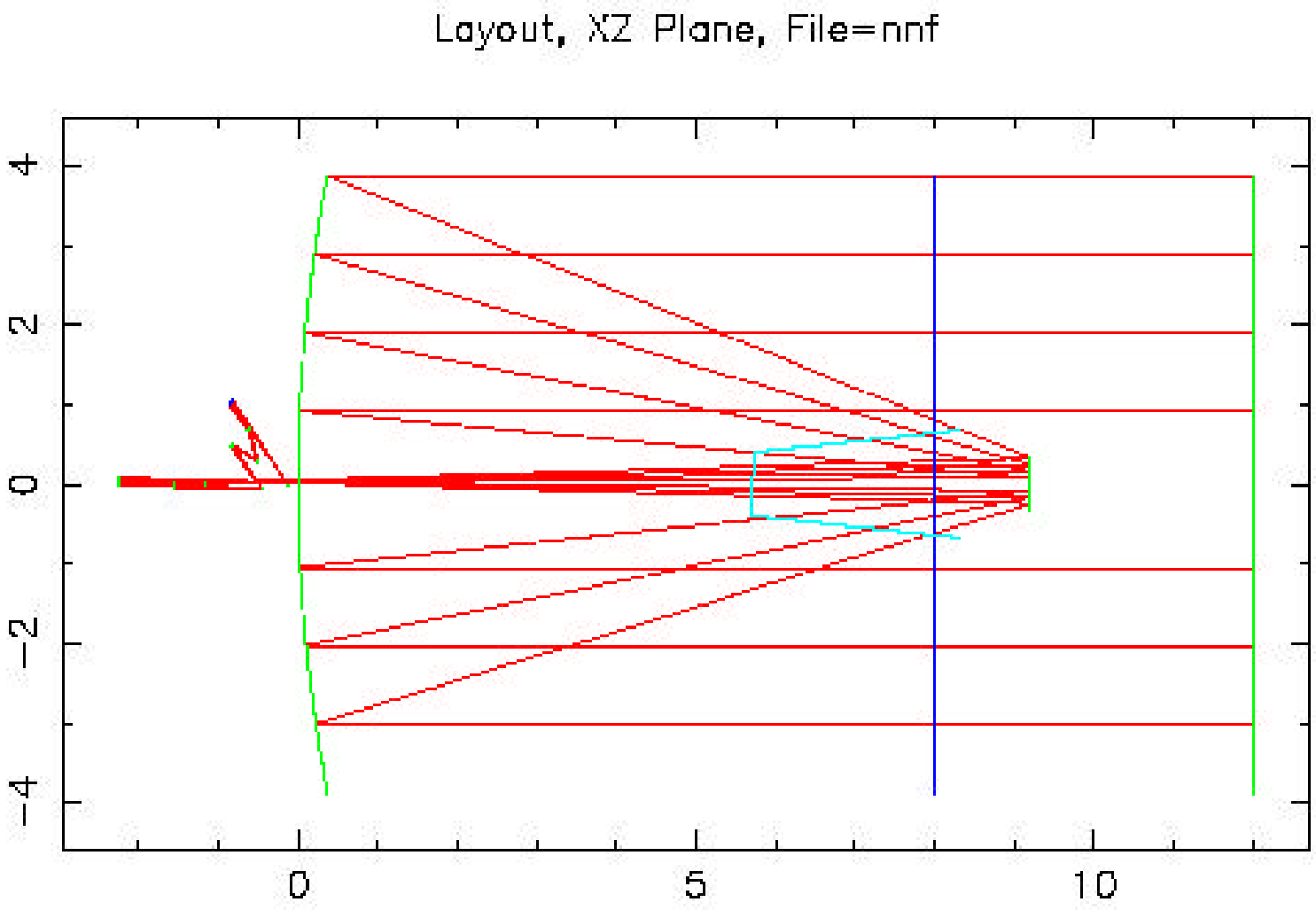
$$u_1 = -G\, w_{est} + du$$

$$G = C_u^{+} = [C_u^{T} C_u]^{-1} C_u$$

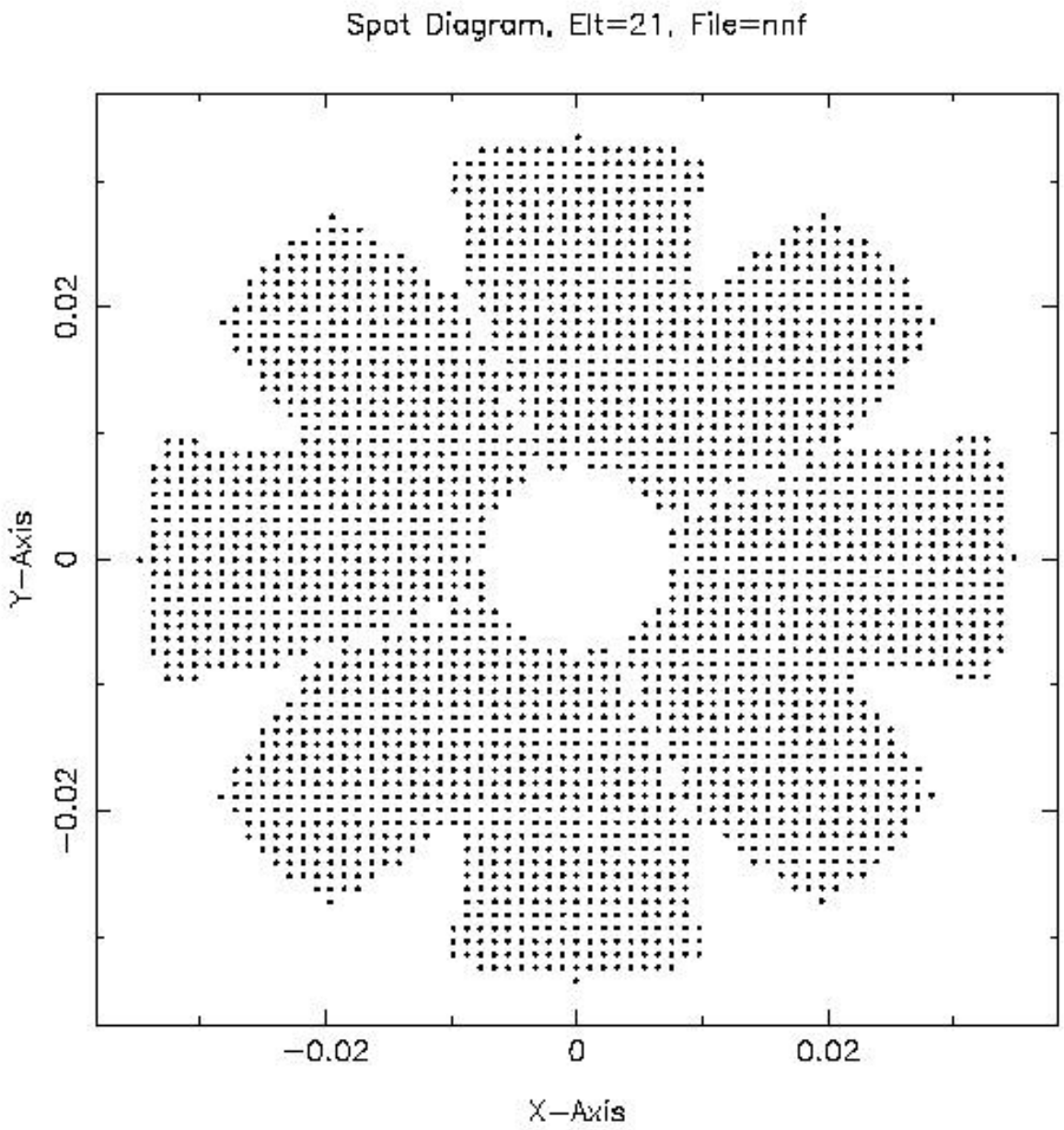
Optical controls

$$u = \begin{bmatrix} u_{segrot} \\ u_{segtrans} \\ u_{SM} \\ u_{dm} \\ \vdots \end{bmatrix}$$

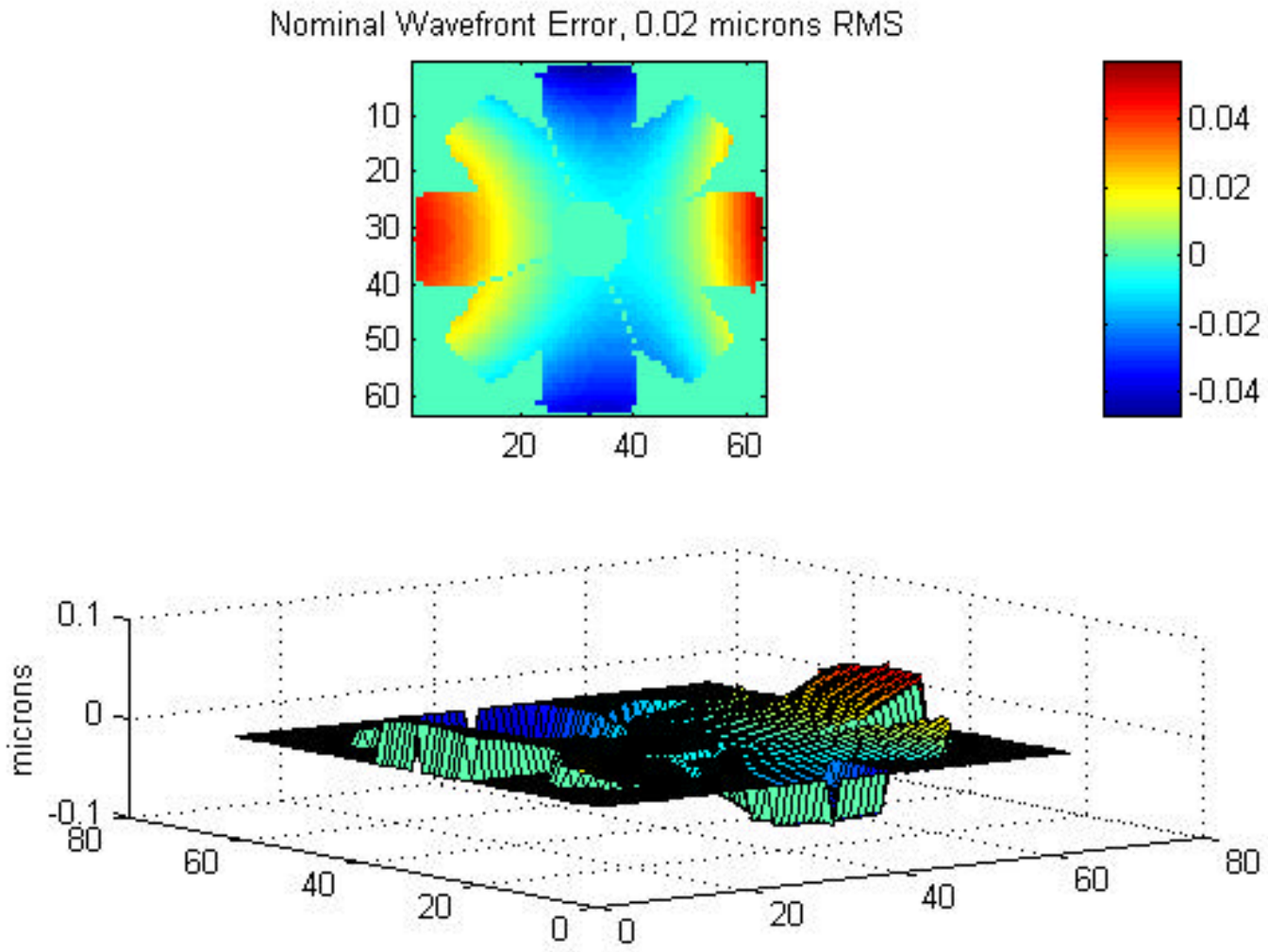
MACOS Ray Trace Model



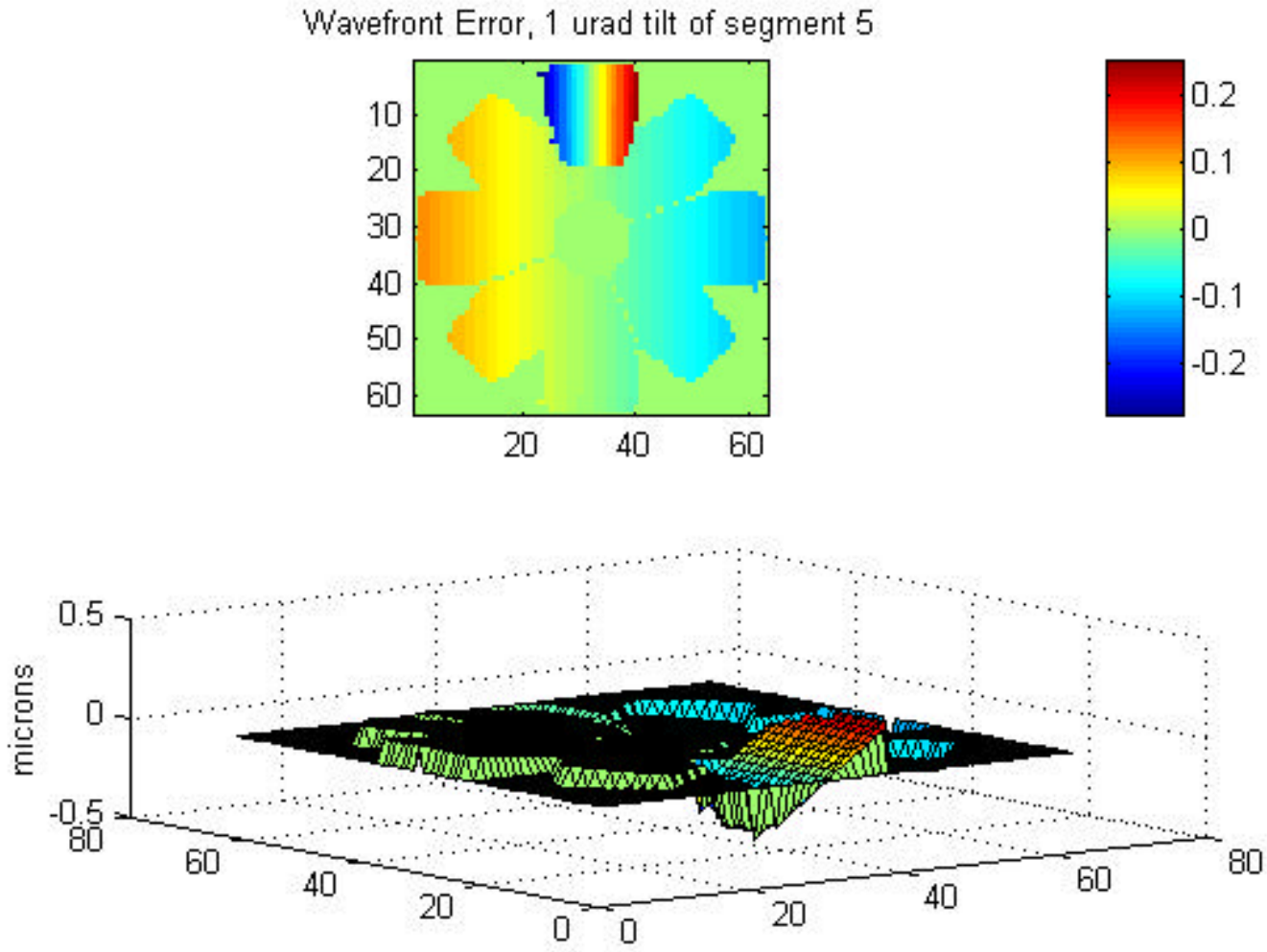
MACOS Spot Diagram



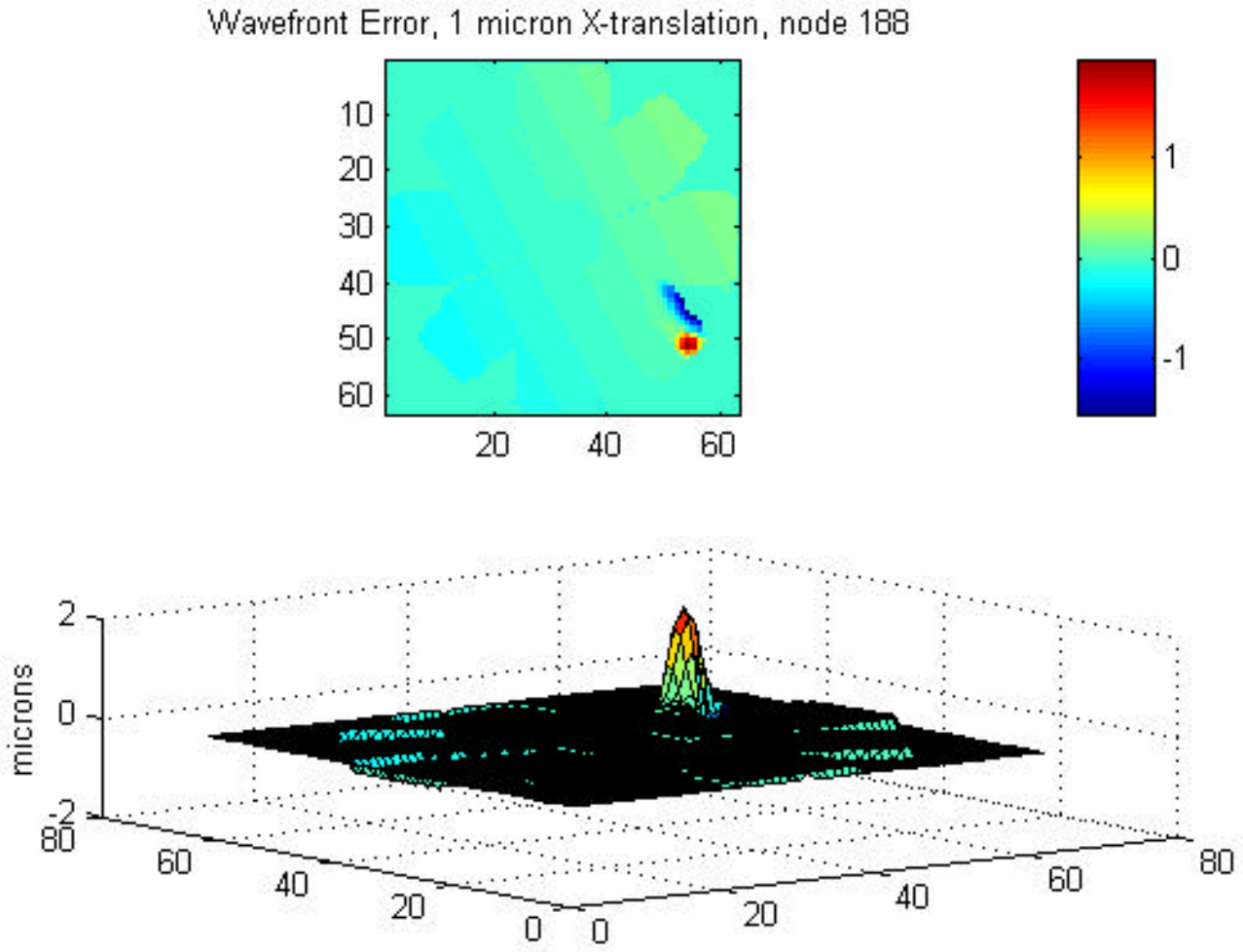
Wavefront Error – Design Residual



Wavefront Error – Segment Tilt



Wavefront Error – FEM Node Translation

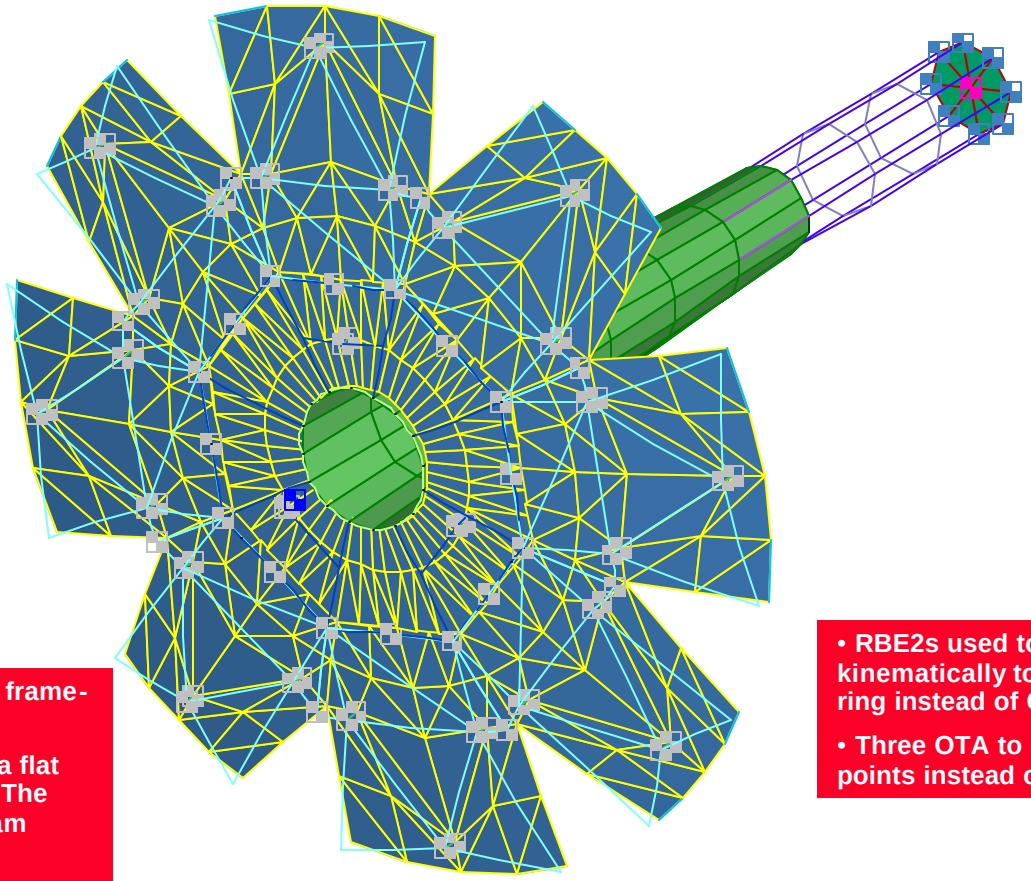


OTA FEM

• recover 1044 DOFs (344 nodes on PM, translation only, plus SM and SI)

• 2.00mm thick face sheet by 4cm deep core orthogrid beryllium mirror shell

•cells are 14.5 cm on a side equilateral triangles,cell wall are 1.00 mm thick



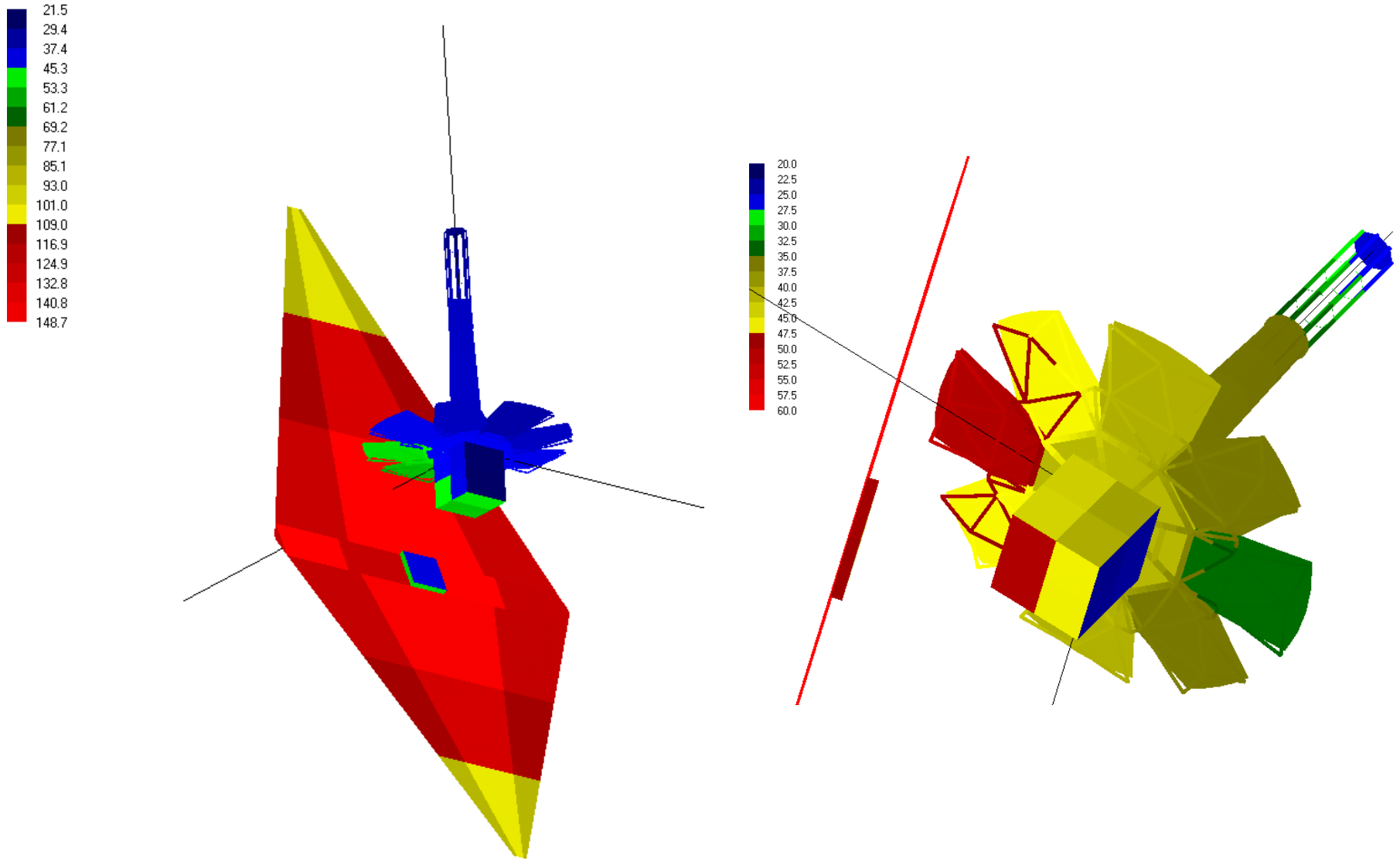
•The petal reaction structure is a beryllium frame-work of I-beams

• The center segment reaction structure is a flat Beryllium frame with a 1.3M dia inner ring. The frame is composed of a 152 mm deep I-beam inner ring and 152mm by 100mm wide box section outer ring and spokes.

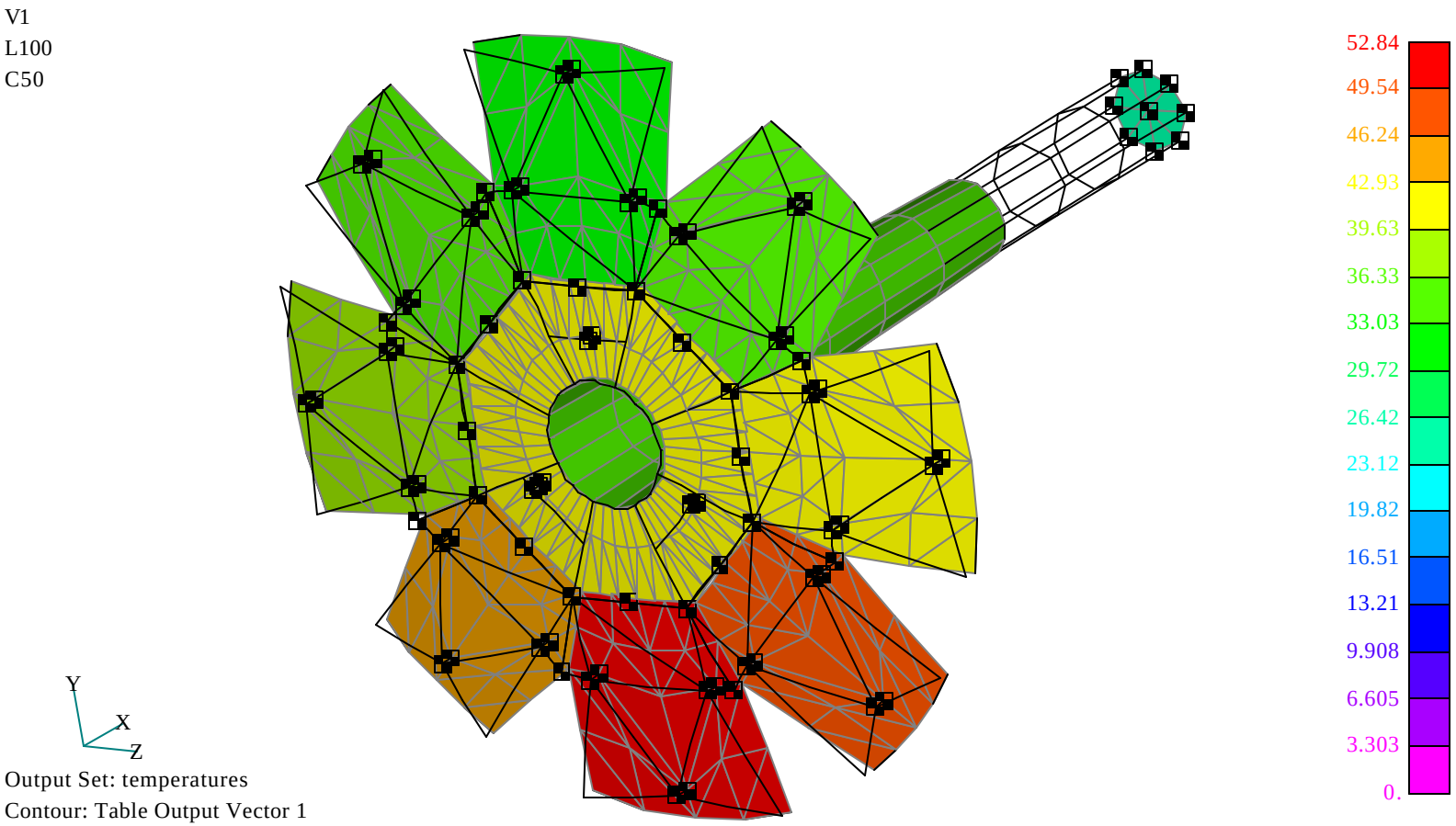
• RBE2s used to attach SI kinematically to center main ring instead of CELAS

• Three OTA to S/C I/F points instead of four

Observatory Thermal Model – Steady State



Steady State Temps Mapped on OTA FEM



Mapping made possible by one-to-one nodalization !!!

Computing the Transformation from Nodal Temperatures to Displacements

- **Net Force Balance: $\{r_{net}\} = 0 = -Ku + \{r_{Temp}\}$**

  Where $\{r_{Temp}\} = \int B^T E \{e_0\} dV = Ku$

  B = standard strain-displacement matrix

  $\{\varepsilon_0\}$= temperature induced strain vector, f (α,temp)

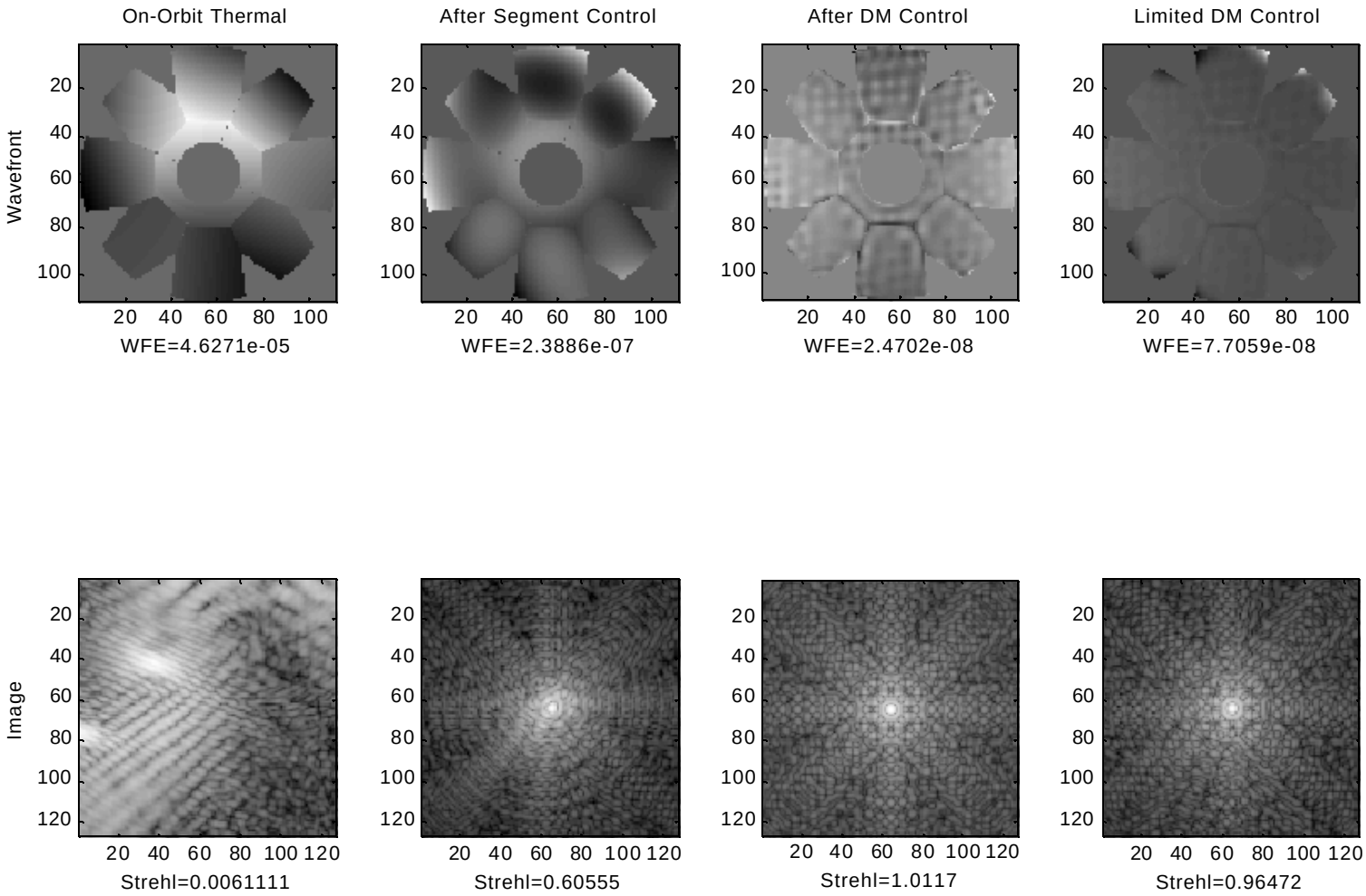
- **We can factor out nodal temperatures, generating a temp to load transformation matrix**
  - **$\{r_{Temp}\} = \{r_g\} = [A_{gg}]\{t_g\}$**

    Where $\{t_g\}$ = nodal temperature (and/or gradient) vector (g-size)

    $\{r_g\}$ = nodal force (and/or moment) vector (g-size)

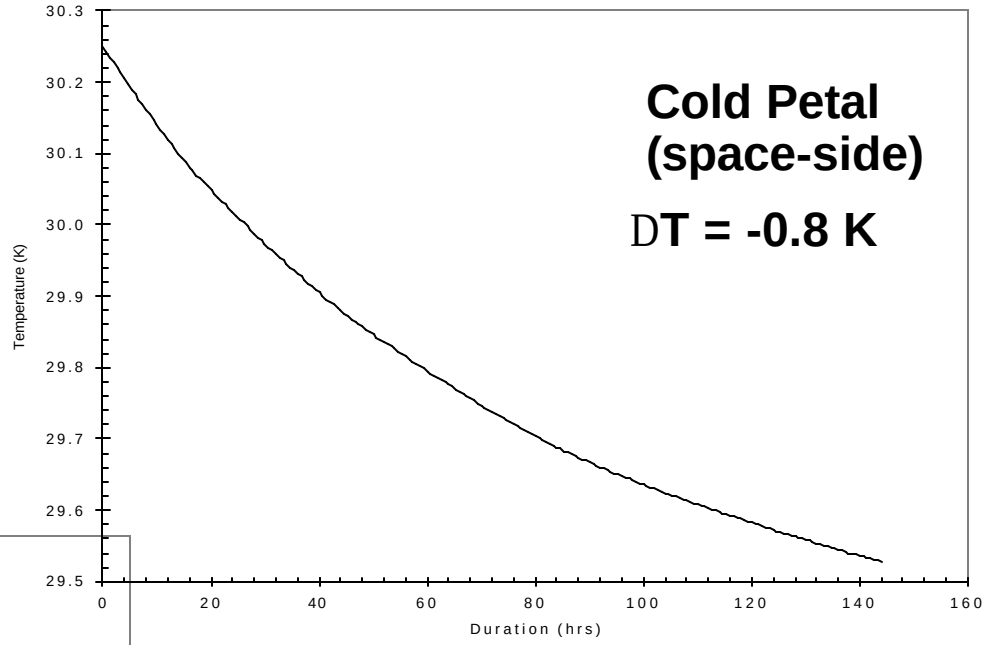
- **Reduce $[A_{gg}]$ to f-set size and transform to Local (NASTRAN global) system**
  - **$[A_{fg}] = [T_{fg}]\ [A_{gg}]$**
- **Premultipy by the flexibility matrix $[K_{ff}]^{-1}$ to get the temperature to displacement transformation matrix G**
  - **$[G_{fg}] = [K_{ff}]^{-1}\ [A_{fg}]$**
- **Expand to g-set, and transform back to the basic coordinate system**
  - **$[G_{gg}] = [T_{fg}]^T\ [G_{fg}]$ or**
  - **$[G_{gg}] = [T_{fg}]^T\ [K_{ff}]^{-1}\ [T_{fg}]\ [A_{gg}]$**
- **So we have the temperature to displacement transformation matrix**
  - **$\{u_g\} = [G_{gg}]\ \{t_g\}$**

Steady State Wavefront Error with Control



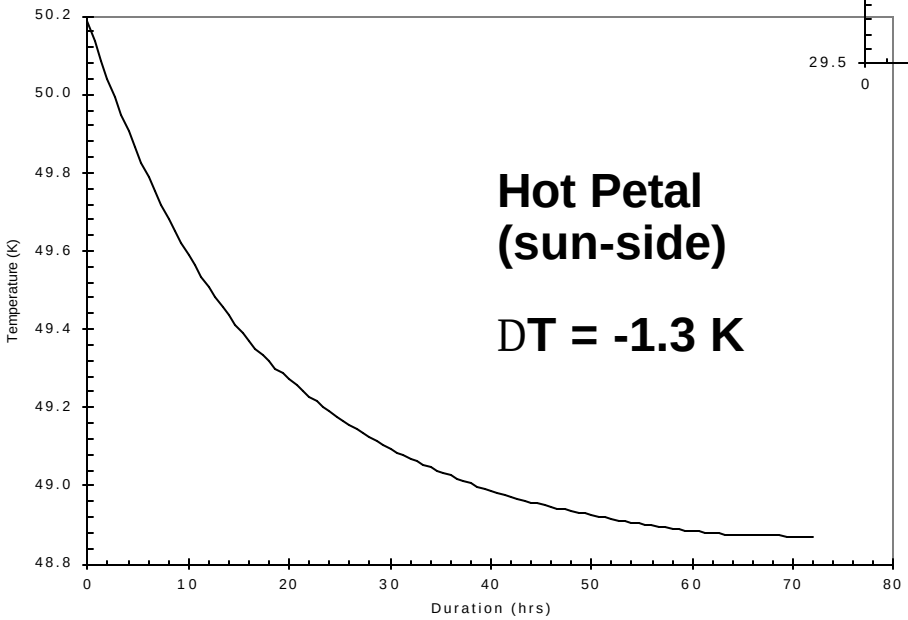
Thermal Transient following 22.5 degree slew

- **Initial attitude has sun normal to sunshield**
- **Final attitude is 22.5 degree pitch away from sun**
- **Thermal equilibrium takes <u>DAYS</u> to reach**



Cold Petal (space-side)

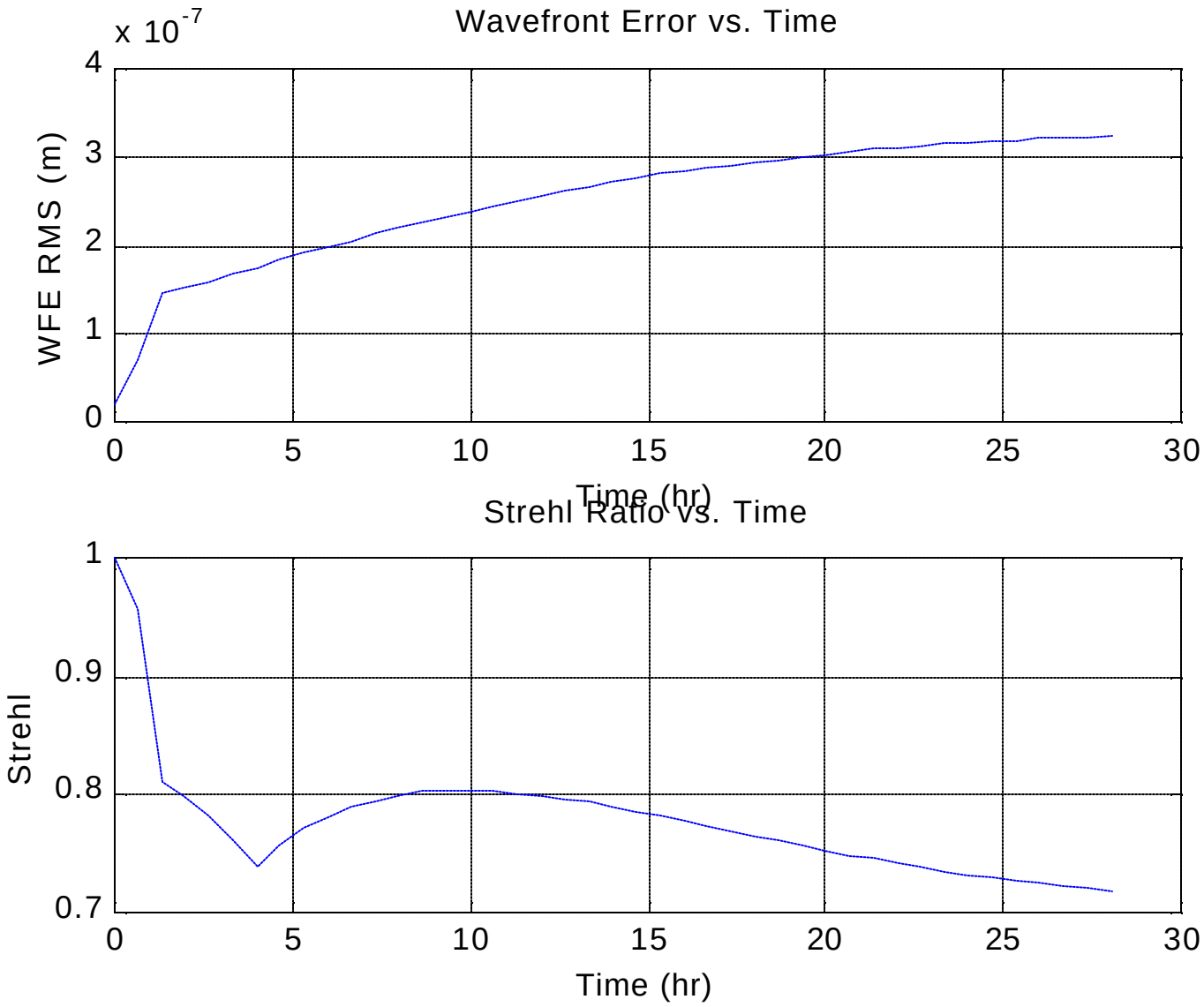
DT = -0.8 K



Hot Petal (sun-side)

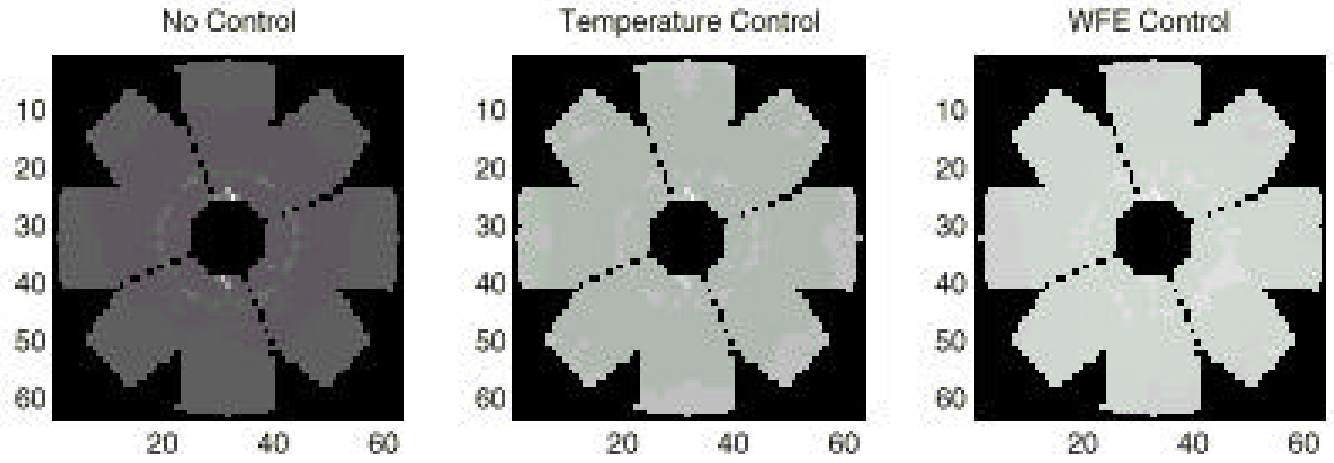
DT = -1.3 K

Thermal Transient Wavefront Error – no Control



Thermal Transient Wavefront Error with Control

Optical Path Difference without control and after control

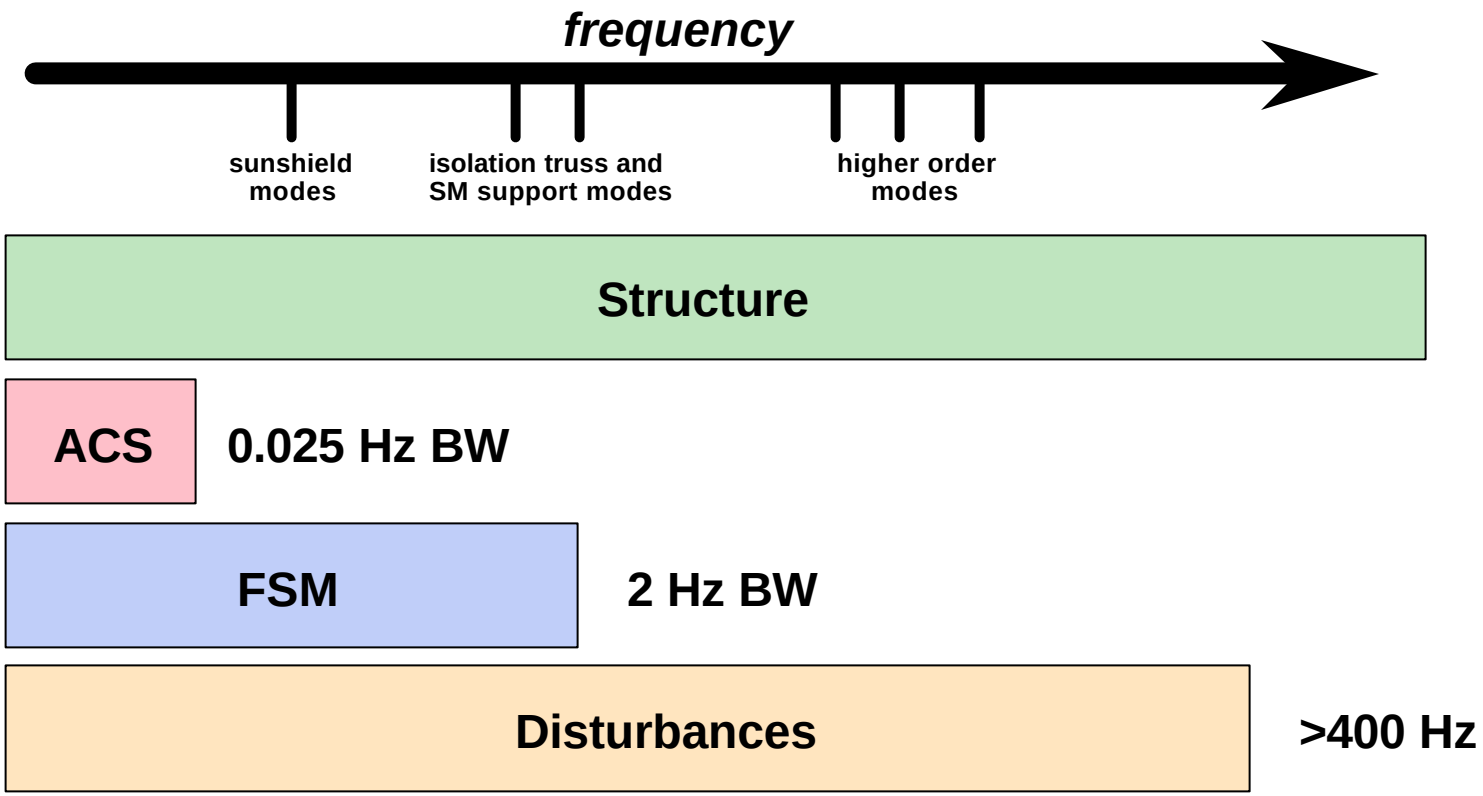


WFE $107.58\,n\mu$ $27.62\,n\mu$ $27.77\,n\mu$

Jitter Analysis

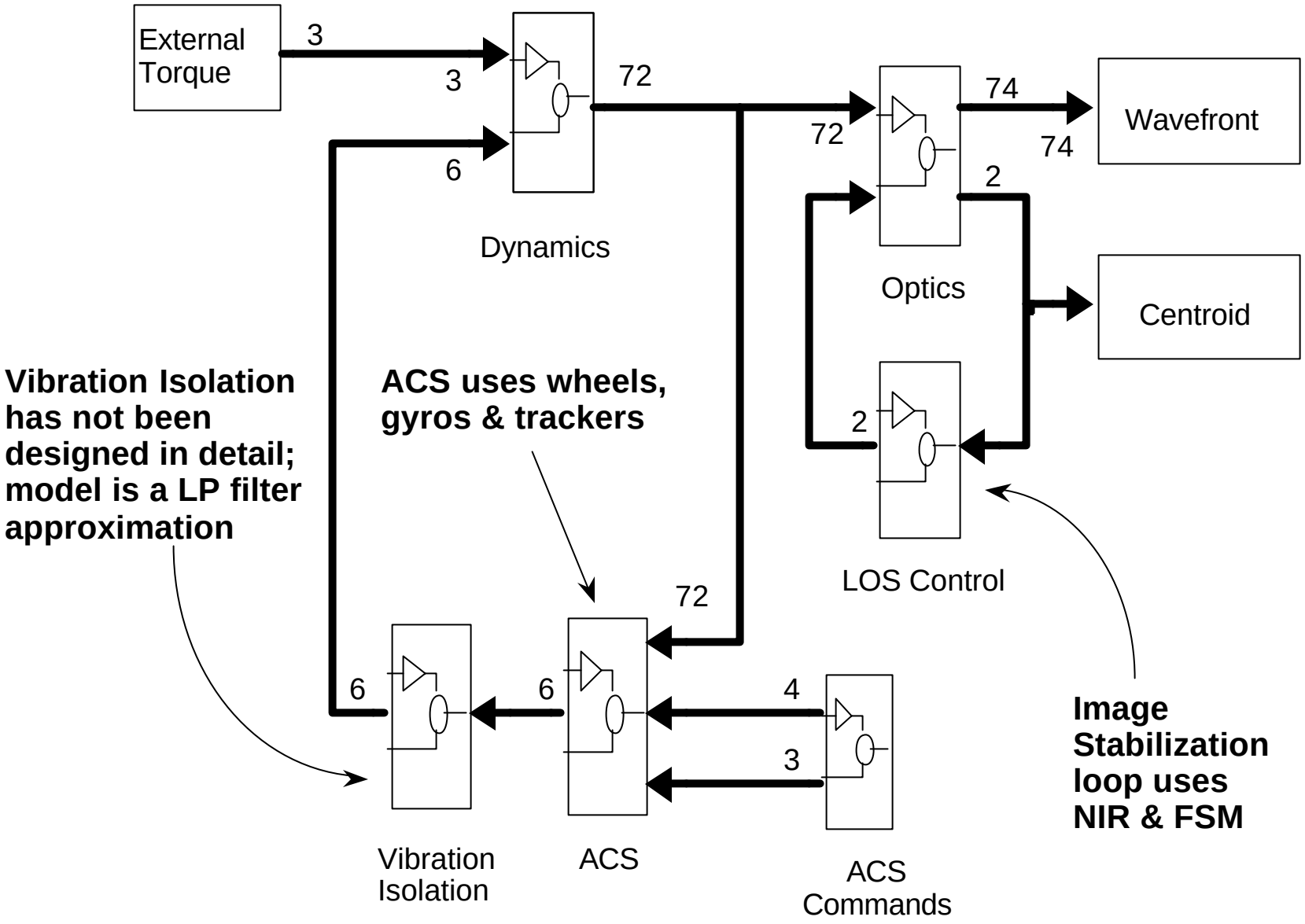
- Pointing Control Architecture
- Linear Systems Model
- Disturbance Model
- Compensation Model
- Results for parametric studies

The CSI Challenge for NGST

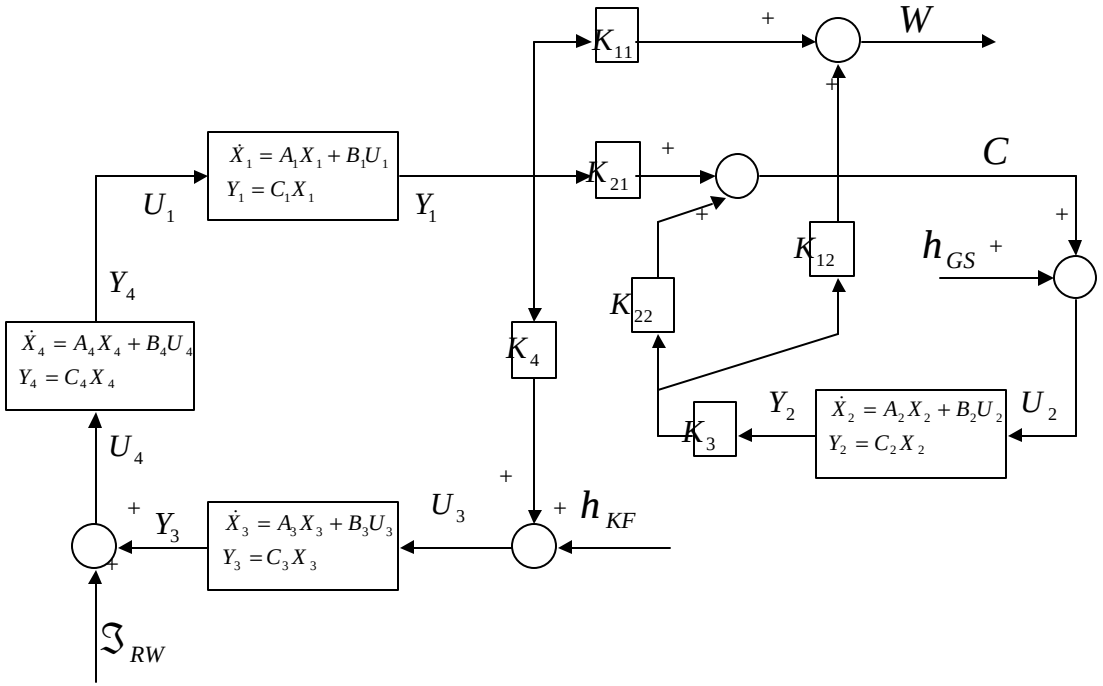


- Lightweight, flexible structure with very low damping limits ACS bandwidth
- FSM bandwidth limited due to guiding sensor noise
- Thermal environment presents challenges to “smart structures” solutions for active damping and vibration suppression

System Level Block Diagram



State-Space Model



$$\dot{X} = AX + BU$$

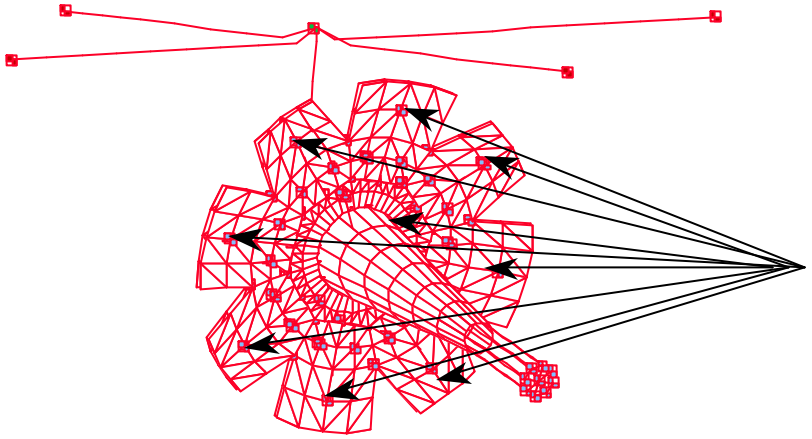
$$Y = CX$$

$$s_W = \sqrt{\frac{W^T W}{N_{rays}}} \qquad s_C = \sqrt{C^T C}$$

$$A = \begin{bmatrix} A_1 & 0 & 0 & B_1C_4 \\ B_2K_{21}C_1 & A_2 + B_2K_{22}C_2 & 0 & 0 \\ B_3K_4C_1 & 0 & A_3 & 0 \\ 0 & 0 & B_4C_3 & A4 \end{bmatrix} \qquad X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} \qquad U = \begin{bmatrix} h_{GS} \\ h_{KF} \\ \Im_{RW} \end{bmatrix} \qquad Y = \begin{bmatrix} W \\ C \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ B_2 & 0 & 0 \\ 0 & B_3 & 0 \\ 0 & 0 & B_4 \end{bmatrix} \qquad C = \begin{bmatrix} K_{11}C_1 & K_{12}C_2 & 0 & 0 \\ K_{21}C_1 & K_{22}C_2 & 0 & 0 \end{bmatrix}$$

Dynamics Model Sensor & Actuator Locations



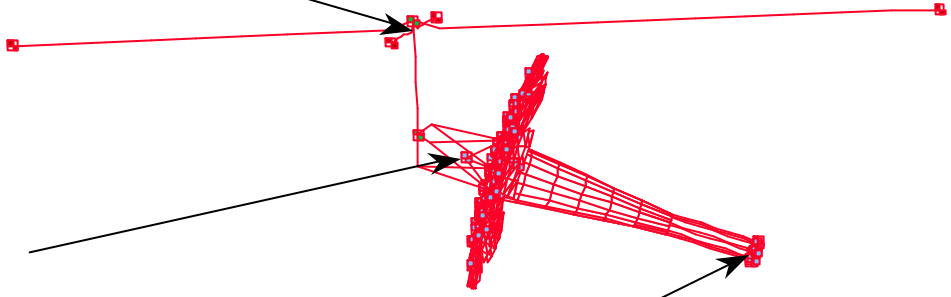
Model size is ~ 5400 DOF; only 71 DOF are required for jitter model

PM (900-908)

These grid points are located at the center of the primary and in a circle with radius 2.8 meters, connected to mirror grid points by RBE2 elements

ACS (10291)

ST, IRU, RWA are co-located



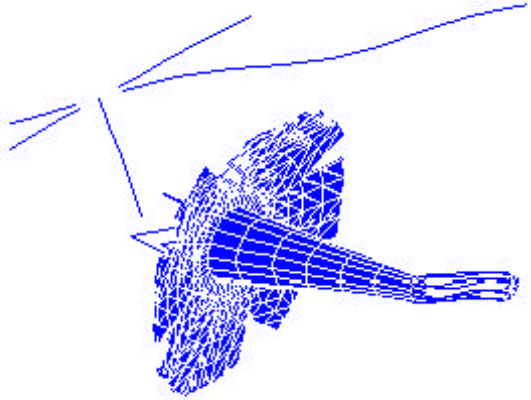
ISIM (825)

FSM, DM, other optics are co-located

SM (829)

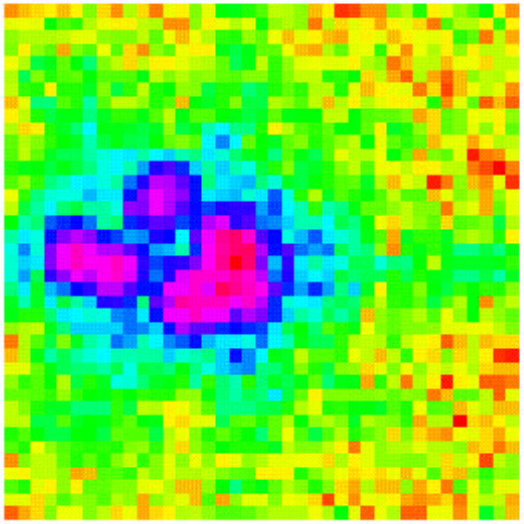
Optomechanical Analysis

Deformed FEM

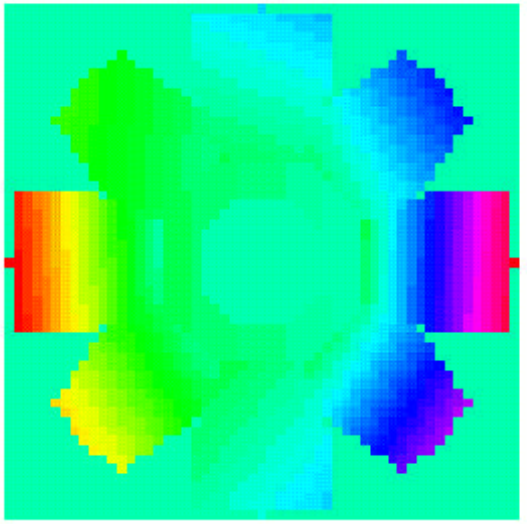


Structural dynamics (mode shapes) and the associated optical distortions are displayed as animations for qualitative analysis

Image (log stretch)



Wavefront Error

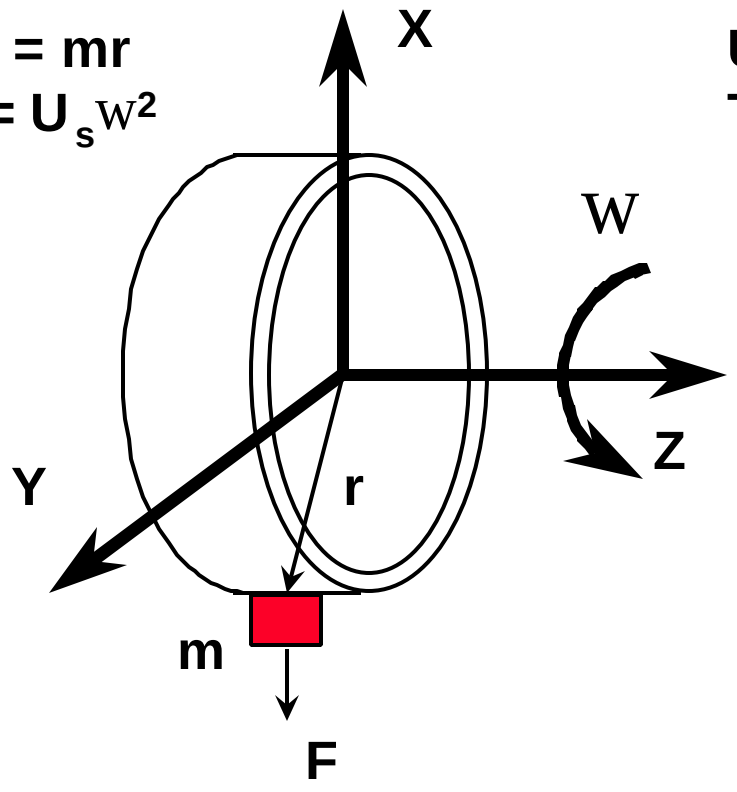


Reaction Wheels are Dominant Disturbances

Static Imbalance

$U_s = mr$

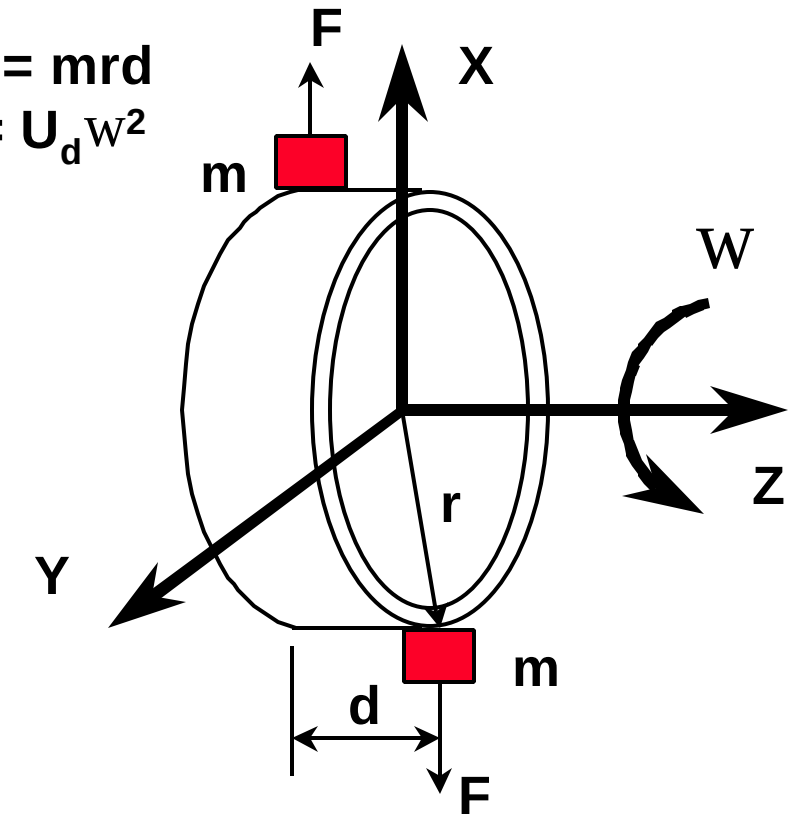
$F = U_s w^2$



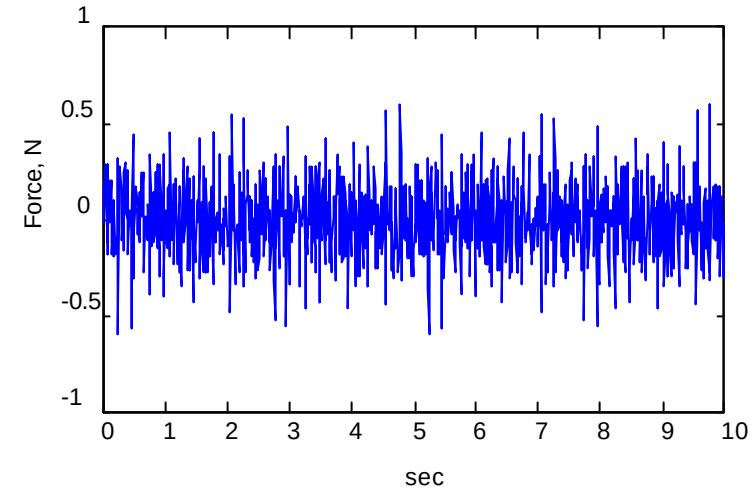
Dynamic Imbalance

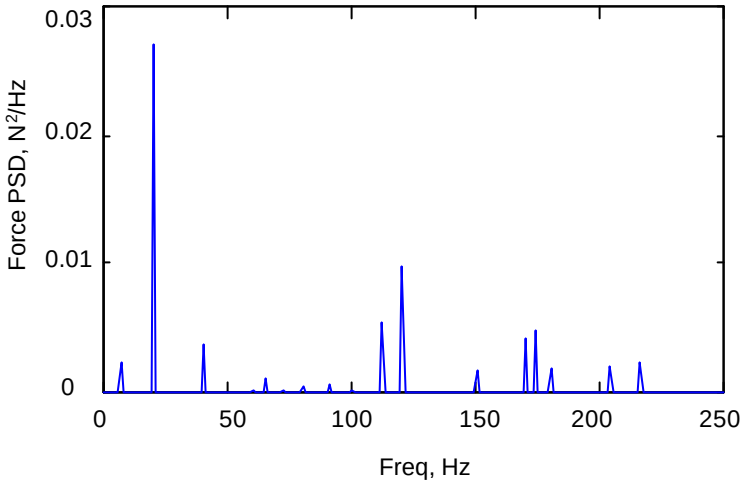
$U_d = mrd$

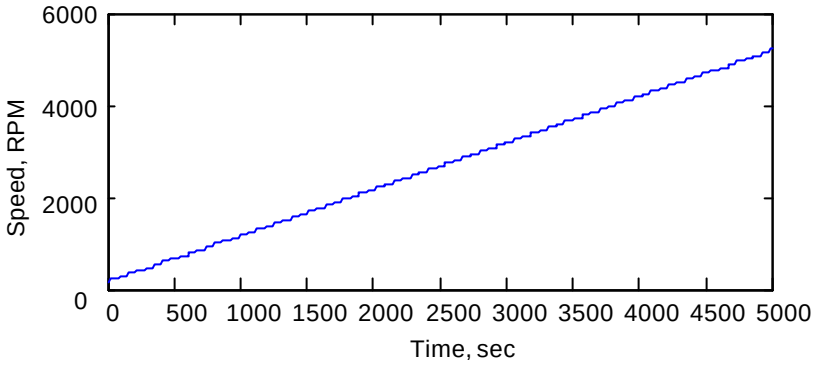
$T = U_d w^2$

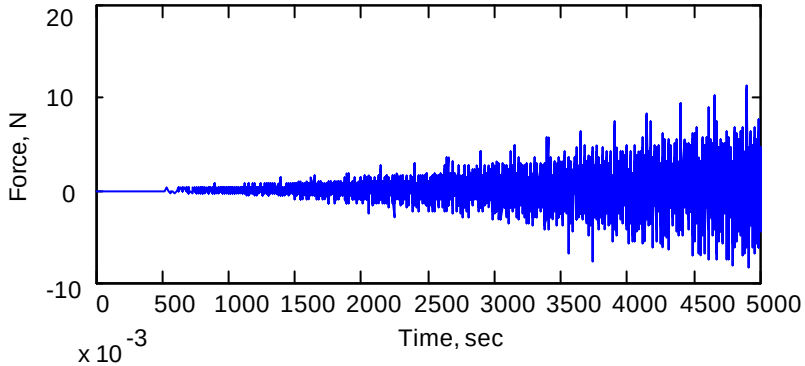


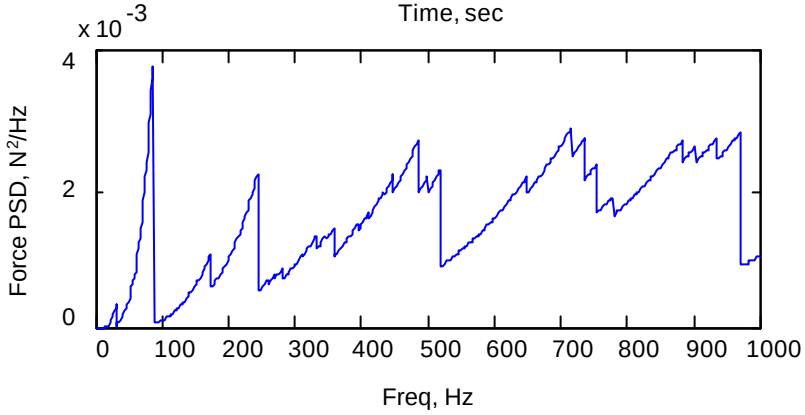
Wheel Disturbances - Discrete Speed vs Swept Speed



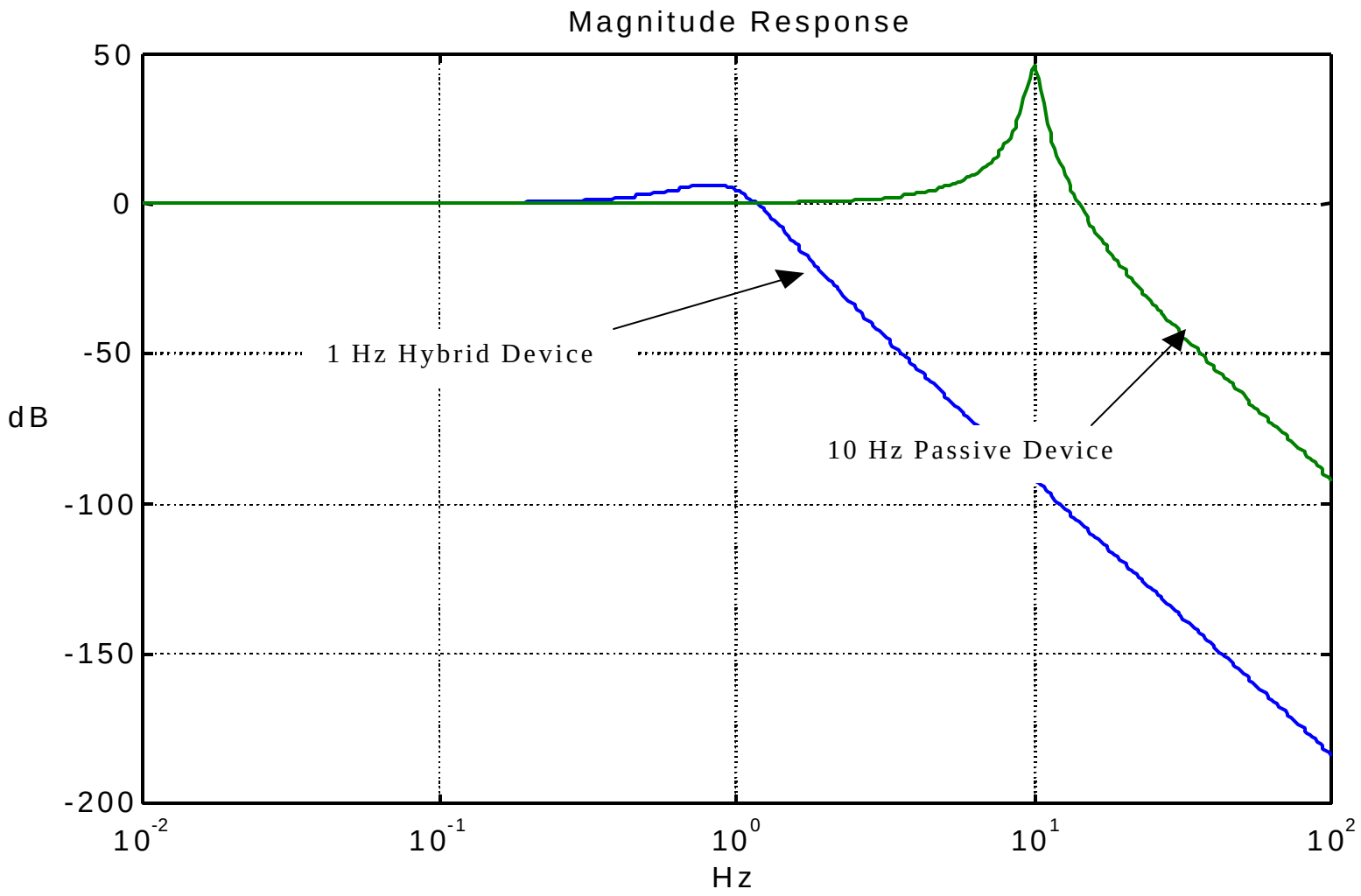




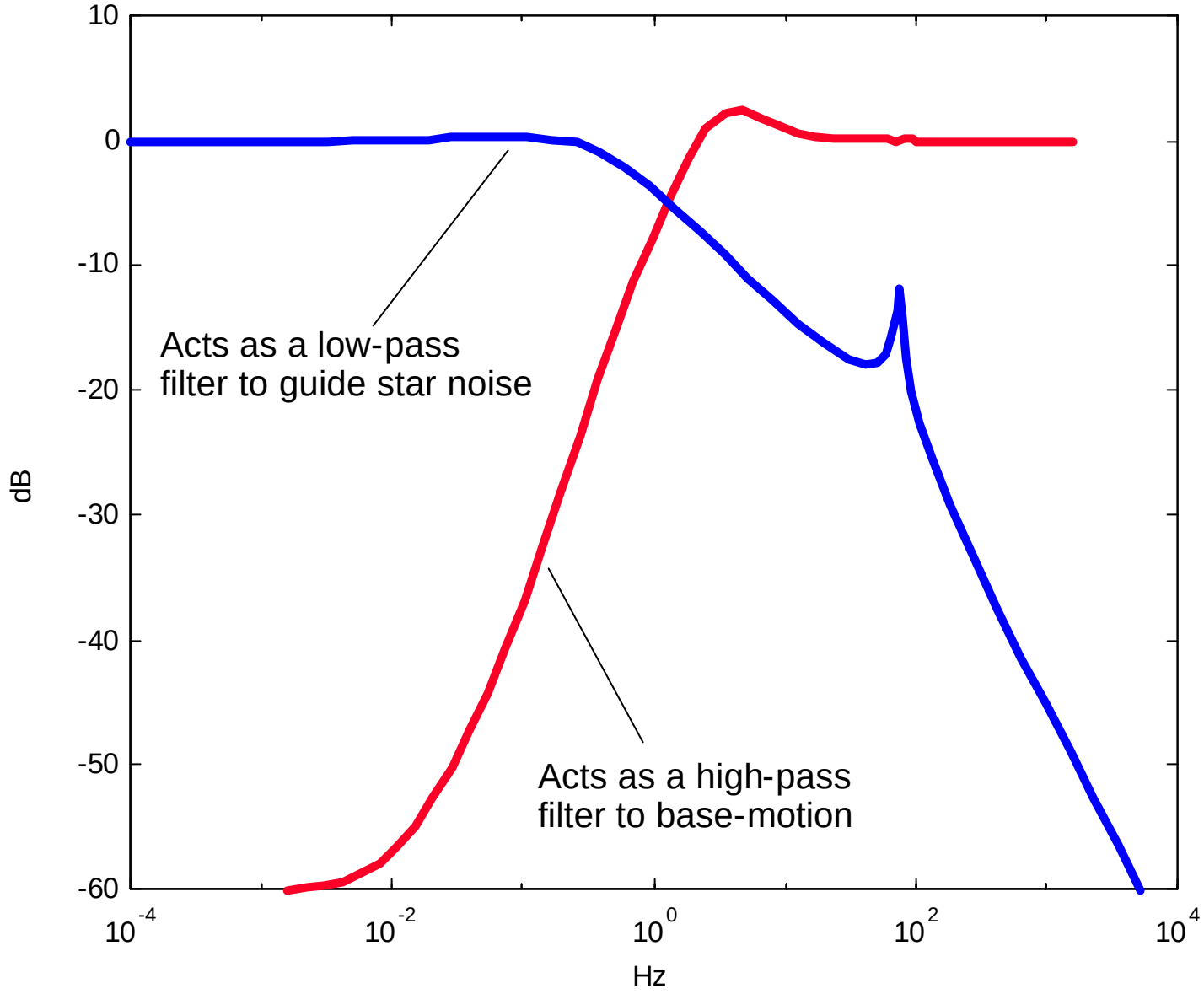




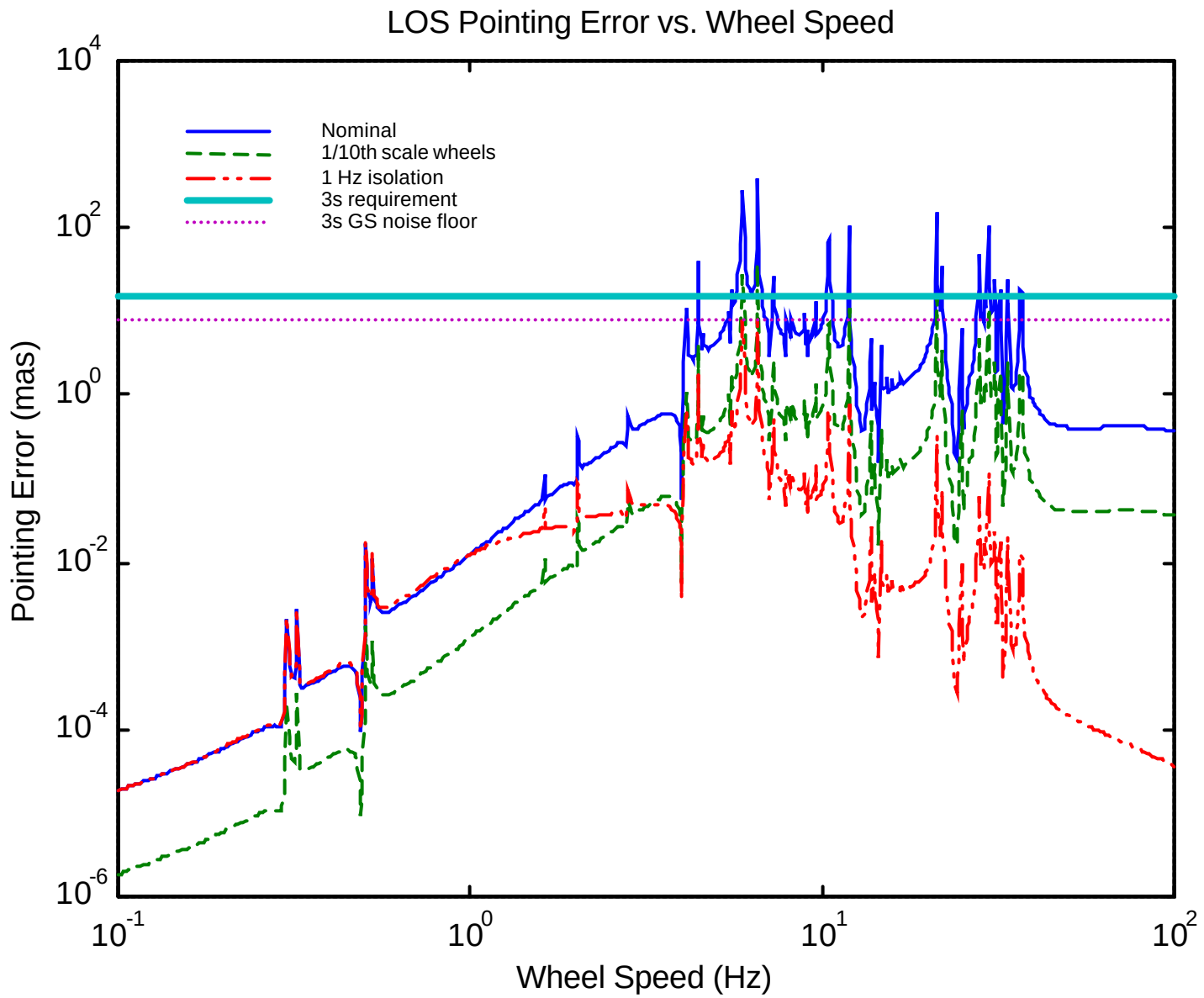
Reaction Wheel Isolation



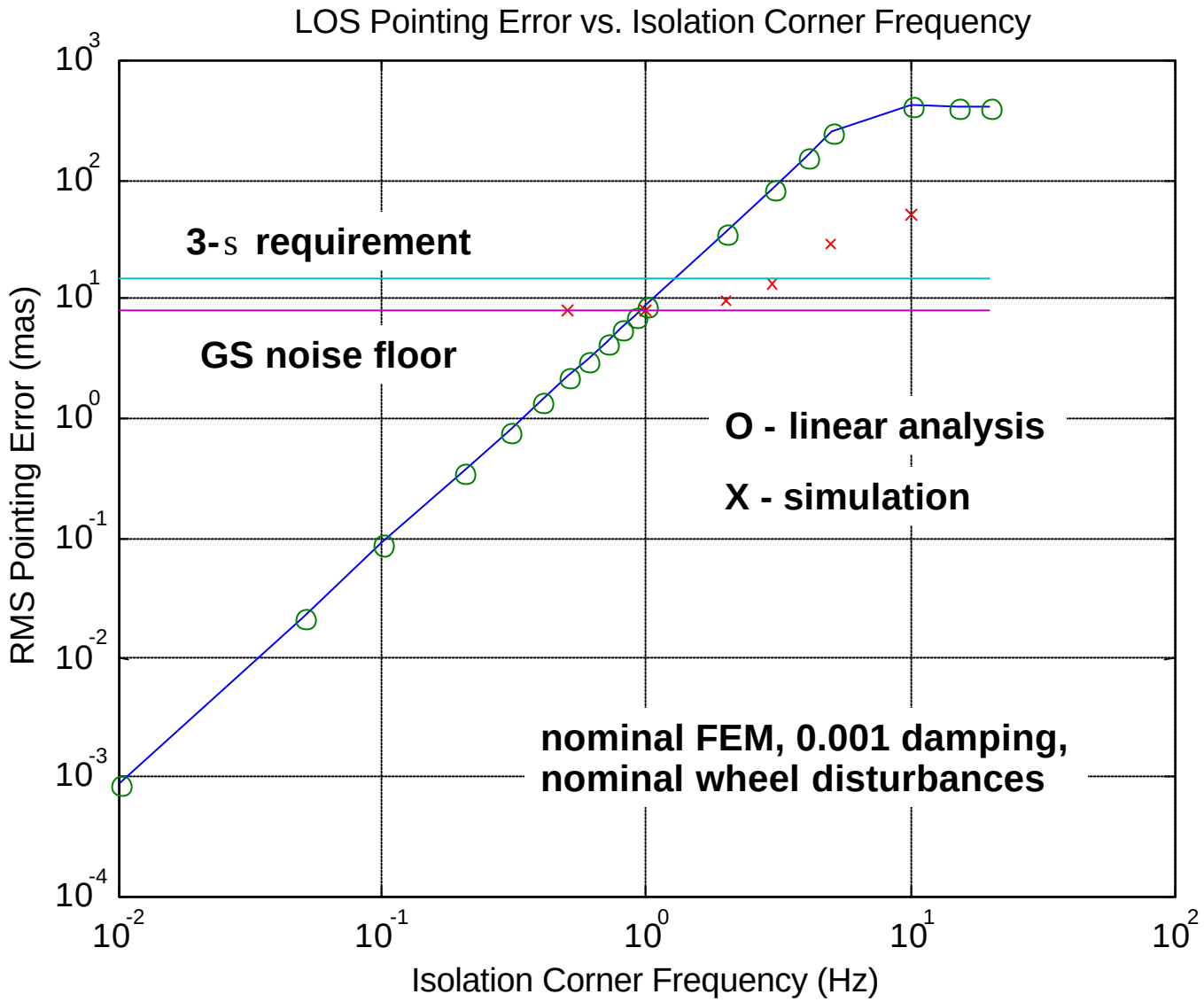
FSM Response Functions



Linear Analysis - Nominal Response, Effect of Isolation, Effect of Wheel Imbalance Amplitude



How Much Isolation Is Required?



Conclusions

- Development of end-to-end models using the IMOS environment was relatively painless, owing to the following factors:
  - translation from NASTRAN and SINDA was possible for FEM and TMM, as was output to FEMAP neutral format
  - geometric and material properties were easily parameterized, as were all other significant entities in the models
  - ray-trace code (MACOS) was open-source, so it could be integrated via Mex-function API
  - Matlab™ is a matrix-oriented language/tool, with integrated graphics and visualization
- Questions remain about the ability to handle realistically-sized models within Matlab™ (eigenvalues, matrix inversion)
- None of these models have been validated, of course…