Performance Analysis of the NGST “Yardstick” Concept via Integrated Modeling

Gary Mosier, Keith Parrish, Michael Femiano
NASA Goddard Space Flight Center

David Redding, Andrew Kissil, Miltiadis Papalexandris
Jet Propulsion Laboratory

Larry Craig, Tim Page, Richard Shunk
NASA Marshall Space Flight Center

August 2000
NGST “Yardstick” Concept

- Deployable secondary mirror
- “Open” telescope (no external baffling) allows passive cooling to 50K
- Beryllium primary mirror
- Large (200m^2) deployable sunshield protects from sun, earth and moon
- Space support module (attitude control, communications, power, data handling) is on warm side
- Science Instruments
- Isolation truss
Model contains ~5400 DOF

Integrated Science Instrument Module

isolation truss

OTA

sunshield short booms

spacecraft module

sunshield long booms

Observatory FEM
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

Encircled Energy
- Stray light
- Jitter
- WFS&C
- Wide-angle scatter
- Detection effects

WF error
- Post-WFS&C optical aberrations
- OTA actuator performance
- OTA figure & alignment
- IM figure & alignment
- Imaging performance

OTA mechanical
- OTA structure
- OTA optics
IM structure
- IM optics

System imaging performance
System EE, SR budget

WF C subsystem WFE budget
Non-WF C subsystems WFE budget
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**

**Linear optical model**

\[ w_0 = C_x x + C_u u_0 \]

**WF sensing**

\[ w_{est} = w_0 + dw_{est} \]

**Control**

\[ u_1 = -G w_{est} + du \]

\[ G = C_u^+ = [C_u^T C_u]^{-1} C_u \]
MACOS Ray Trace Model
MACOS Spot Diagram

Spot Diagram, Elt=21, File=nnf

X-Axis

Y-Axis
Wavefront Error – Design Residual

Nominal Wavefront Error, 0.02 microns RMS
Wavefront Error – Segment Tilt

Wavefront Error, 1 urad tilt of segment 5
Wavefront Error – FEM Node Translation
OTA FEM

- 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
- RBE2s used to attach SI kinematically to center main ring instead of CELAS
- Three OTA to S/C I/F points instead of four

- The petal reaction structure is a beryllium framework 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.

- Recover 1044 DOFs (344 nodes on PM, translation only, plus SM and SI)
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: \( \{ r_{\text{net}} \} = 0 = -Ku + \{ r_{\text{Temp}} \} \)
  
  Where \( \{ r_{\text{Temp}} \} = \int B^T E \{ \varepsilon_0 \} \, dV = Ku \)
  
  \( B \) = standard strain-displacement matrix
  
  \( \{ \varepsilon_0 \} = \) temperature induced strain vector, \( f(\alpha, \text{temp}) \)

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

  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
  
  \( [A_{fg}] = [T_{fg}] [A_{gg}] \)

- Premultiply 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
  
  \( [G_{gg}] = [T_{fg}]^T [G_{fg}] \) \quad \text{or} \quad [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

On-Orbit Thermal
- WFE = 4.6271e-05
- Strehl = 0.0061111

After Segment Control
- WFE = 2.3886e-07
- Strehl = 0.60555

After DM Control
- WFE = 2.4702e-08
- Strehl = 1.0117

Limited DM Control
- WFE = 7.7059e-08
- Strehl = 0.96472
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 DAYS to reach

Cold Petal (space-side)
\[ \Delta T = -0.8 \, \text{K} \]

Hot Petal (sun-side)
\[ \Delta T = -1.3 \, \text{K} \]
Thermal Transient Wavefront Error – no Control

Wavefront Error vs. Time

Strehl Ratio vs. Time
Thermal Transient Wavefront Error with Control

Optical Path Difference without control and after control

No Control  | Temperature Control  | WFE Control

WFE 107.58 \( \mu \) | 27.62 \( \mu \) | 27.77 \( \mu \)
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

External Torque → Dynamics → Optics → Wavefront

Dynamics

Vibration Isolation

ACS uses wheels, gyros & trackers

ACS Commands

Image Stabilization loop uses NIR & FSM

Centroid

Vibration Isolation has not been designed in detail; model is a LP filter approximation
State-Space Model

\[
\dot{X} = AX + BU
\]

\[
Y = CX
\]

\[
\sigma_W = \sqrt{W^TW} \quad \sigma_C = \sqrt{C^TC}
\]

\[
A = \begin{bmatrix}
A_1 & 0 & 0 & B_1C_4 \\
B_2K_2C_1 & A_2 + B_2K_2C_2 & 0 & 0 \\
B_3K_4C_1 & 0 & A_3 & 0 \\
0 & 0 & B_4C_3 & A_4 \\
\end{bmatrix}
\]

\[
X = \begin{bmatrix}
X_1 \\
X_2 \\
X_3 \\
X_4 \\
\end{bmatrix}
\]

\[
U = \begin{bmatrix}
\eta_{GS} \\
\eta_{KF} \\
\zeta_{RW} \\
\end{bmatrix}
\]

\[
Y = \begin{bmatrix}
W \\
C \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 & 0 & 0 & 0 \\
B_2 & 0 & 0 & 0 \\
0 & B_3 & 0 & 0 \\
0 & 0 & B_4 & 0 \\
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
K_{11}C_1 & K_{12}C_2 & 0 & 0 \\
K_{21}C_1 & K_{22}C_2 & 0 & 0 \\
\end{bmatrix}
\]
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.

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

\[ U_s = mr \]
\[ F = U_s \omega^2 \]

Dynamic Imbalance

\[ U_d = mrd \]
\[ T = U_d \omega^2 \]
Wheel Disturbances - Discrete Speed vs Swept Speed
Reaction Wheel Isolation

Magnitude Response

- Frequency: 1 Hz Hybrid Device
- Frequency: 10 Hz Passive Device

Decibels (dB) vs. Frequency (Hz)
Acts as a high-pass filter to base-motion

Acts as a low-pass filter to guide star noise
Linear Analysis - Nominal Response, Effect of Isolation, Effect of Wheel Imbalance Amplitude

LOS Pointing Error vs. Wheel Speed

- Nominal
- 1/10th scale wheels
- 1 Hz isolation
- 3s requirement
- 3s GS noise floor

Pointing Error (mas)

Wheel Speed (Hz)
How Much Isolation Is Required?

LOS Pointing Error vs. Isolation Corner Frequency

- 3-σ requirement
- GS noise floor
- O - linear analysis
- X - simulation

nominal FEM, 0.001 damping, nominal wheel disturbances
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…