Multidisciplinary Analysis of the NEXUS Precursor Space Telescope

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Problem Setting

Traditionally: Define System Parameters $p_j = p_o$ → Predict $H_2$ performances $J_{z,i}$

Isoperformance: Find Locus of Solutions $p_{LB} < p_j < p_{UB}$ ← Constrain performances $J_{z,i} = J_{z,req}$
Purpose of this case study:

Demonstrate the usefulness of Isoperformance on a realistic conceptual design model of a high-performance spacecraft

The following results are shown:

- Integrated Modeling
- Nexus Block Diagram
- Baseline Performance Assessment
- Sensitivity Analysis
- Isoperformance Analysis (2)
- Multiobjective Optimization
- Error Budgeting

NGST Precursor Mission
2.8 m diameter aperture
Mass: 752.5 kg
Cost: 105.88 M$ (FY00)
Target Orbit: L2 Sun/Earth
Projected Launch: 2004
Nexus Integrated Model

Legend:
Design Parameters
(I/O Nodes)

Spacecraft bus
(84) m_bus
8 m² solar panel
RWA and hex isolator (79-83) K_rISO

sunshield I_ss

Instrument (207)

2 fixed PM petals (149,169) K_yPM

2 deployable PM petals (129) K_zpet

SM spider t_sp
SM (202) m_SM

Cassgrain Telescope:
PM (2.8 m)
PM f/# 1.25
SM (0.27 m)
f/24 OTA

Structural Model (FEM)
(Nastran, IMOS) Ω, Φ
Nexus Block Diagram

Number of performances: $n_z = 2$
Number of design parameters: $n_p = 25$

Number of states $n_s = 320$
Number of disturbance sources: $n_d = 4$

\[ x' = Ax + Bu \]
\[ y = Cx + Du \]
Initial Performance Assessment $J_z(p^o)$

Results

<table>
<thead>
<tr>
<th>Lyap/Freq</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{z,1}$ (RMMS WFE)</td>
<td>25.61</td>
</tr>
<tr>
<td>$J_{z,2}$ (RSS LOS)</td>
<td>15.51</td>
</tr>
</tbody>
</table>

Centroid Jitter on Focal Plane [RSS LOS]

Requirement: $J_{z,2}=5$ [$\mu$m]
Nexus Sensitivity Analysis

Graphical Representation of Jacobian evaluated at design \( p_o \), normalized for comparison.

\[
\nabla J_z = \frac{p_o}{J_{z,o}} \begin{bmatrix}
\frac{\partial J_{z,1}}{\partial R_u} & \frac{\partial J_{z,2}}{\partial R_u} \\
\vdots & \ddots & \ddots \\
\frac{\partial J_{z,1}}{\partial K_{cf}} & \frac{\partial J_{z,2}}{\partial K_{cf}}
\end{bmatrix}
\]

**RMMS WFE most sensitive to:**
- Ru - upper op wheel speed [RPM]
- Sst - star track noise 1\(\sigma\) [asec]
- K_rISO - isolator joint stiffness [Nm/rad]
- K_zpet - deploy petal stiffness [N/m]

**RSS LOS most sensitive to:**
- Ud - dynamic wheel imbalance [gcm²]
- K_rISO - isolator joint stiffness [Nm/rad]
- zeta - proportional damping ratio [-]
- Mgs - guide star magnitude [mag]
- Kcf - FSM controller gain [-]
2D-Isoperformance Analysis

Isoperformance contour for RSS LOS: \( J_z, \text{req} = 5 \ \mu \text{m} \)

Parameter Bounding Box

Initial design

Test

Spec

HST

K_rISO RWA isolator joint stiffness [Nm/rad]

K_rISO [Nm/rad]

Ud = mrd [gcm²]

E-wheel

Isolated strut

Joint

CAD Model

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Nexus Multivariable Isoperformance \( n_p = 10 \)

Pareto-Optimal Designs \( p^* \)

Design A

Best “mid-range” compromise

Design B

Smallest FSM control gain

Design C

Smallest performance uncertainty

Performance

<table>
<thead>
<tr>
<th>Jz,1</th>
<th>Jz,2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design A</td>
<td>20.0000</td>
</tr>
<tr>
<td>Design B</td>
<td>20.0012</td>
</tr>
<tr>
<td>Design C</td>
<td>20.0001</td>
</tr>
</tbody>
</table>

Cost and Risk Objectives

<table>
<thead>
<tr>
<th>Jc,1</th>
<th>Jc,2</th>
<th>Jr,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design A</td>
<td>0.6324</td>
<td>0.4668</td>
</tr>
<tr>
<td>Design B</td>
<td>0.8960</td>
<td>0.0017</td>
</tr>
<tr>
<td>Design C</td>
<td>1.5627</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

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## Nexus Error Budgeting

### LTI System, $J_{z,\text{req}}$, $p_{\text{bounds}}, p_{\text{nom}}$

### Isoperformance Toolbox

### Error Source Contributions

### Plot Error Contribution Sphere

\[ \Psi_i = \sum_{j=1}^{n_d} \Psi_{i,j} = J_{z,\text{req},i}^2 \]

#### Error Source Budget

<table>
<thead>
<tr>
<th>Error Source</th>
<th>VAR %</th>
<th>Allocation</th>
<th>VAR %</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWA</td>
<td>50.00</td>
<td>3.535534</td>
<td>0.01</td>
<td>0.4988912</td>
</tr>
<tr>
<td>Cryocooler</td>
<td>25.00</td>
<td>2.500000</td>
<td>0.00</td>
<td>0.2439626</td>
</tr>
<tr>
<td>Attitude Noise</td>
<td>5.00</td>
<td>1.118034</td>
<td>0.00</td>
<td>7.564E-06</td>
</tr>
<tr>
<td>GStar Noise</td>
<td>20.00</td>
<td>2.236068</td>
<td>0.99</td>
<td>5.1715676</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>5.000000</td>
<td></td>
<td>5.2013</td>
</tr>
</tbody>
</table>

Note: ACS sensor noise contributions not shown.
Nexus Initial $p^\circ$ vs. Final Design $p^{**}_{iso}$

Parameters | Initial | Final |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ru$</td>
<td>3000</td>
<td>3845</td>
</tr>
<tr>
<td>$Us$</td>
<td>1.8</td>
<td>1.45</td>
</tr>
<tr>
<td>$Ud$</td>
<td>60</td>
<td>47.2</td>
</tr>
<tr>
<td>$Qc$</td>
<td>0.005</td>
<td>0.014</td>
</tr>
<tr>
<td>$Tgs$</td>
<td>0.040</td>
<td>0.196</td>
</tr>
<tr>
<td>$KrISO$</td>
<td>3000</td>
<td>2546</td>
</tr>
<tr>
<td>$Kzpet$</td>
<td>0.9E+8</td>
<td>8.9E+8</td>
</tr>
<tr>
<td>$tsp$</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>$Mgs$</td>
<td>15</td>
<td>18.6</td>
</tr>
<tr>
<td>$Kcf$</td>
<td>2E+3</td>
<td>4.7E+5</td>
</tr>
</tbody>
</table>

Improved system characteristics include:

- **Initial:** $14.97 \mu m$
- **Final:** $5.155 \mu m$

Improvements are achieved by a well balanced mix of changes in the disturbance parameters, structural redesign and increase in control gain of the FSM fine pointing loop.
Paper Conclusions

• For new generation of lightweight, deployable telescopes such as NGST and NEXUS the disciplines of structures, optics and controls are coupled and must be considered together during early design stages.

• Performance predictions can be made for “engineering” metrics such as WFE, LOS jitter etc that flow down from science requirements. These predictions are based on integrated models, but are uncertain and depend on many assumptions.

• Nevertheless one can gain valuable insights from sensitivity analysis to identify key driving system parameters.

• Isoperformance seeks not the best achievable performance, but acceptable performance, while balancing the burden among subsystems.

• Error budgeting and Integrated Modeling can be linked.